PETROLEUM RECOVERY INSTITUTE

NON-THERMAL RECOVERY OF HEAVY AND MEDIUM OILS IN THIN RESERVOIRS BY USE OF USING GRADED VISCOSITY BANK

(PART OF ENERGY, MINES & RESOURCES COST-SHARED ENERGY CONVERSION PROGRAM AND PART OF THE PROGRAM OF THE FEDERAL PANEL ON ENERGY R&D (PERD))

FINAL REPORT

BY

HEMANTA K. SARMA, BRIJ B. MAINI AND F. NICOLA

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Hemanta K. Sarma, Brij B. Maini and F. Nicola
Petroleum Recovery Institute
Calgary, Alberta, Canada T2L 2A6

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EXECUTIVE SUMMARY

Because of excessive heat losses to the overlying and underlying strata, thermal recovery methods are not well suited for thin reservoirs. In this study, the use of miscible solvent flooding as an alternative to thermal methods in such reservoirs was investigated. The effects of viscous instabilities, and the effectiveness of graded viscosity banks in minimizing the extent of viscous instabilities in miscible flooding were evaluated.

Three different types of miscible displacement processes were investigated using a visual rectangular scaled-physical model packed with glass beads: (i) displacement of oil with pure solvent, (ii) displacement using viscosity-graded slugs of oil and solvent (Claridge, 1978), and (iii) displacement using linearly-graded slugs of oil and solvent (Coskuner and Bentsen, 1987).

It was observed, that both methods of viscosity grading reduced the extent of viscous instabilities significantly. Of the three types of displacements carried out, displacements with linearly-graded slugs were most effective in minimizing viscous instabilities during displacements. However, with regard to the recovery efficiency of the in situ oil, both types of viscosity-graded slugs were not economic because the produced oil was used as a component in the injected slugs. As a consequence, it is concluded that the graded viscosity banks for miscible solvent flooding can become economically successful only when a cheaper method of increasing the viscosity of the solvent becomes available.

SOMMAIRE EXECUTIF

Les méthodes de récupération thermiques ne sont pas bien adaptées aux réservoirs que l'on dit minces. Les pertes de chaleur excessives, lesquelles se dissipent dans les couches inférieures et supérieures, en sont la cause. Cette étude démontre que les déplacements de solvent miscible offrent une alternative viable aux méthodes thermiques. On évalua le comportement des instabilitées visqueuses ainsi que l'efficacité des banques d'huile à viscosité graduée sur la minimization des instabilitées visqueuses dans les déplacements miscibles.

Trois types de procédés de déplacement miscible furent étudiés, à l'aide d'un modèle poreux composé de verre granulé:(i) déplacement d'huile à l'aide d'un solvent pure, (ii) déplacement à l'aide de bouchons d'huile à viscosite graduée et solvent (Claridge, 1978), et (iii) déplacement à l'aide de bouchons d'huile à viscosité linéaire et solvent (Coskuner et Bentsen, 1987).

Ainsi, on a observé que les méthodes à viscosité graduée peuvent réduire, d'une manière significative, les instabilitées visqueuses. Parmi les trois types de déplacements essayés, les déplacements avec bouchons d'huiles à viscosité linéaire réussirent le mieux à minimizer les instabilitées visqueuses lors des déplacements. Cependant, en ce qui concerne l'efficacité de récupération des huiles in situ, les deux types de bouchons à viscosité graduée ne sont pas économiquement viable. parce que l'huile produite fut utilisée comme un constituant des bouchons injectés. Par conséquent, on peut conclure que la banque d'huile à viscosité graduée, pour un déplacement de solvent miscible, peut devenir économiquement avantageuse seulement lorsqu'une méthode moins couteuse pour augmenter la viscosité des solvents sera disponible.

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1.0 Introduction

Although thermal recovery methods seem to be obvious choices for recovering much of about 1,000 MMSTB of medium and heavy oils in Alberta and Saskatchewan, it is recognized that, in many reservoirs, such recovery methods are not feasible for a number of techno-economic reasons. Many of these reservoirs are thin and/or very heterogeneous. As a consequence, excessive heat losses to the overlying and underlying formations occur. Furthermore, significant heat losses can also occur due to the presence of fractures and channels, and other reservoir heterogeneities.

Miscible flooding has received considerable attention in recent years because of its inherent potential to achieve higher recovery efficiency. A survey by Thomas *et. al.* (1989) suggests that miscible flooding was the most popular method with operators in the U.S.A. during 1980-81. However, because of the high material and operational costs associated with the continual injection of the solvent slug, such process has become less attractive at the present competitive oil prices, and polymer flooding has now taken over as the most popular flooding technique in the U.S.A.

In most displacement processes, miscible or immiscible, reservoir heterogeneities and adverse viscosity ratios between the *in situ* fluid and solvent make the displacement unstable causing viscous fingers to grow at the displacement front. Such instability in a displacement process can seriously curtail the sweep efficiency and make the process inefficient and uneconomic. Therefore, it is important to understand the phenomenon of viscous

fingering in porous media in an attempt to minimize its effects.

In spite of numerous works reported in literature on viscous fingering, it still remains one of the most intriguing and challenging phenomena for scientists and engineers to understand and control (Homsy, 1987). As stated earlier, one of the major reasons why viscous fingers develop at the displacement front is the adverse mobility ratio between the displaced and the displacing fluids. Unlike immiscible displacements, the fingers in miscible displacements do not form a sharp interface at the front, but rather a transition zone due to diffusion and dispersion of the fluids. Formation of such a zone, whose composition exhibits continuous gradation due to blending, arrests fingering of displacing fluid to some extent (Sarma, 1986). If, however, such a zone does not form in the field situation, particularly in the initial stages of the solvent injection, severe viscous fingering may occur. Hence, the primary objective in the graded-viscosity bank concept is to achieve a continuous gradation in the composition within the transition zone at the front. In practice, this is achieved by following the injection of the solvent slug with a series of chase fluids such that there is a gradual decrease in the viscosity away from the front. This practice, known as "viscosity grading", has been practiced in polymer floods. There are two major advantages to be gained from the use of a graded-viscosity bank. First, it minimizes, if not eliminates all together, viscous fingering, and second, it facilitates use of a smaller solvent slug thereby cutting the projects costs substantially.

Koning *et. al.* (1988) have reported a substantial savings (about 17%) in polymer costs in a polymer flood project in the Marmul field of Oman. Ligthelm (1989) suggests that this saving can be increased further by 30-40% by adopting a grading scheme with a larger number of steps.

However, the graded-viscosity bank concept should not be regarded as a panacea to all reservoir situations. According to Lake (1989), the concept of graded viscosity becomes economic only when the mobility ratio is very high and/or the formation is very heterogeneous.

2.0 Literature Review

The first experimental study of the concept of graded-viscosity bank can be credited to Weinaug and Ling (1959). However, their study was based on a single Hele-Shaw type experiment using a quarter of five-spot type model. A year later, in 1960, Slobod and Lestz reported laboratory studies on porous sand-pack to demonstrate that graded viscosity bank helped minimize viscous fingering. Because the viscosity of a fluid mixture was dependent on its composition, the desired gradation in the viscosity was achieved by changing the composition of the mixture gradually. By introducing small volumes of fluids intermediate in composition in between the *in situ* and displacing fluid, they demonstrated that a significant reduction in viscous fingering could be achieved. Furthermore, they also observed that use of a continuous blended zone rather than step-wise viscous gradation completely eliminated viscous fingering.

Perrine (1961 a,b) proposed a stability theory to optimize the solvent recovery of oil by defining the limiting conditions required for a stable miscible displacement, and to estimate the minimum solvent slug size required. Later in 1965, Kyle and Perrine conducted an experimental study to validate Perrine's theory and concluded that the concentration gradient criterion proposed in Perrine's theory was an order of magnitude higher than what was observed in experiments.

Koval (1963) proposed a method for predicting the performance of unstable immiscible displacements in heterogeneous media combining the effects of a number of factors, such as, viscosity ratio, channeling and longitudinal dispersion. This method, which is analogous to the Buckley-Leverett method (Buckley and Leverett, 1942), is referred to as the K-factor method. Because Koval's work form the basis of many recent studies pertaining to the graded-viscosity bank concept, it is prudent to review his work in further details.

Koval identified six important factors which could cause a miscible displacement process to become unstable, such as:(i) longitudinal dispersion (including geometrical effects), (ii) channeling, (iii) viscosity ratio between the displacing and displaced fluids, (iv) gravitational effects due to the difference in densities, (v) diffusion, and (vi) flooding rate. Koval did not study the effects of the last two factors because they were thought to be of less importance at the high flooding rates (15 ft/day) employed in his experiments. Furthermore, to keep the analysis simple and tractable, he imposed several simplifying

conditions and assumptions, such as: (i) the system used was linear, (ii) solvent was miscible in oil in all proportions, and was injected continuously into the porous medium, and (iii) gravity effects were negligible due to the use of fluids of equal densities.

The K-factor defined by Koval is essentially the product of two other parameters, the heterogeneity factor (H) and effective viscosity ratio (E). The heterogeneity factor, H, in Koval's analysis is a lumped factor which includes the effects of dispersion and channeling due to variations in the permeability. Because the longitudinal dispersion is dependent on the length of the system, this factor inherently incorporates the effect of the the length of the system as well. In Koval's K-factor method, a heterogeneous system is defined as the "one in which the recovery at one pore volume solvent injected in a matched viscosity flood is less than 99 per cent". Based on empirical results, Koval developed a defining curve for heterogeneity factor which enabled him to provide a quantitative estimate of the heterogeneity factor, H. For example, for a homogeneous system, H is equal to one, and H increases as the degree of heterogeneity increases. Furthermore, he observed that shorter the length of the core, the higher is the heterogeneity factor. In a recent study, Menzie (1987) found that the H-factors were higher for rocks with higher dispersivity.

In miscible displacements, the solvent and oil are continuously mixed and a transition or mixing zone develops at the interface of the two fluids. When this happens, the viscosity of

the oil changes significantly, and in most cases, the viscosity of the oil decreases. Thus, one can envisage a situation in which oil is driven by a mixture of solvent and oil such that the viscosity of the mixture lies within an intermediate range between that of pure solvent and pure oil. It is, therefore, appropriate to take into account the ratio of the viscosities of the oil to that of the mixture rather than the viscosity ratio between the oil and pure solvent. Koval used this ratio of the viscosities of the oil to that of the solvent mixture, and defined it as the effective viscosity ratio, E. Thus, a single parameter was used to characterize a rather complicated viscosity effect in a miscible displacement. The mathematical definition of E proposed by Koval is:

$$E = (0.78 + 0.22\ V^{1/4})^4 \qquad (1)$$

where, V = viscosity ratio of the pure fluids, μ_o / μ_s.

The above equation for E is based on experimental data obtained from systems in which effects of dispersion and channeling were minimum. The solvent mixture composition used in the equation (78% oil and 22% solvent) was used arbitrarily as this was the composition that seemed to give the best fit of experimental data. By undertaking an approach similar to that of Buckley and Leverett (1942), Koval arrived at the following equation for pore volume recovered (N_{pv}) in a miscible flood:

$$N_{pv} = \frac{2\left(K\,V_{pi}\right)^{1/2} - 1 - V_{pi}}{K-1} \qquad (2)$$

where, V_{pi} = solvent pore volume injected, and K-factor = H x E.

In 1978, Claridge proposed a method for designing graded viscosity banks for minimizing viscous fingering in linear systems. In his method, Koval's empirical K-factor method was utilized repeatedly for each viscosity zone to design the viscosity bank, and an equation underlying the criterion for the minimum size of a continuously graded bank was derived:

$$\lim_{n \to \infty} V_{pv} = (1 - 1/M^{0.44}) \qquad (3)$$

where, V_{pv} is pore volume of the fluid, and M is the mobility ratio between the fluids. In most cases, M>1; therefore, the size of the continuously graded bank will be less than one pore volume in a linear system.

Figure 1 depicts a conceptual illustration of the technique proposed by Claridge. He showed that, if 0, 1, 2, 3, ... were the trailing slugs of displacing fluids with descending viscosities, respectively, the size of a particular slug could be estimated by using the following formula:

$$V_{slug} = \frac{\left[M_n M_{n-1} - 1\right]}{\left[M_n M_{n-1} \cdots M_2 M_1 M_0\right]^2} \qquad (4)$$

Coskuner and Bentsen (1987) proposed a stability theory for miscible displacement processes to obtain a dimensionless number as a function of the dimensions of the porous medium and the

properties of the fluids. The critical value of this dimensionless number, also called the instability number, was utilized to predict the onset of viscous fingering in a miscible displacement process. Using Chuoke's unpublished work reported by Gardner and Ypma in 1984 to account for the boundary conditions at the side walls of the porous model, they demonstrated that this theory could be used to predict the initial length of the transition region between the solvent and the oil.

Because Coskuner and Bentsen assumed that the coefficients of the longitudinal and transverse dispersions were different from one another, they were able to derive an upper and a lower bound for the length of the graded viscosity region. They validated their theory by using data from the literature, but did not report any experimental verification of their theory using a porous medium. The equations for the upper and lower bounds suggested by Coskuner and Bentsen for the length of the graded-viscosity region are as follows:

Upper bound:

$$\Delta Z = \frac{-4k\left(\frac{V}{k}\frac{d\mu}{dc} - \frac{d\rho}{dc}g\right)}{\bar{\mu}\,\phi\,\pi^2 K_1}\,\frac{L_x^2 L_y^2}{L_x^2 + L_y^2} \qquad (5)$$

Lower bound:

$$\Delta Z = \frac{-k\left(\frac{V}{k}\frac{d\mu}{dc} - \frac{d\rho}{dc}g\right)}{\bar{\mu}\,\phi\,\pi^2 K_1}\,\frac{L_x^2 L_y^2}{L_x^2 + L_y^2} \qquad (6)$$

Because of the high material and operational costs, the concept of graded-viscosity bank in miscible flooding is yet to receive an encouraging nod from the industry, particularly in heavy oil reservoirs. Its application has remained confined mainly to polymer floods. Furthermore, only a few field-scale pilot projects using this concept have been reported in the literature (Ligthelm, 1989; Koning *et al.*, 1988; Stoneberger and Claridge, 1988). Although the concept seems to be viable for thin and heterogeneous reservoirs with adverse mobility ratios, it has not been tried in the medium- and heavy-oil reservoirs.

3.0 Objective

The objectives of this study were two-fold: first, to study how viscous instabilities affected cumulative oil recoveries in miscible displacements of heavier oils in a scaled physical model; and second, to demonstrate whether the extent of viscous instabilities can be minimized by using miscible viscosity-graded slugs in such displacements.

In order to meet above objectives, following steps were adopted:

1. A literature survey was conducted and a bibliography of relevant work in this area was prepared.
2. A set of scaling criteria for the process was developed and a physical scaled model that facilitated flow visualization in the porous medium was built.
3. A large number of displacement experiments using fluids with three different viscosity ratios, and at different flow rates

were conducted.

At each chosen displacement rate, miscible displacement runs were carried out for three oils using both the pure solvent and viscosity-graded slugs (Claridge's method) made up of oil and solvent.

Also, miscible displacement runs were conducted by using linearly-graded slugs of solvent and oil (Coskuner and Bentsen method) at one given flow rate for each of the three oils.

4. A comparison of cumulative net oil recoveries from displacements under various experimental conditions was made to demonstrate the extent and effects of viscous instabilities.
5. An economic feasibility study was done based on our experimental findings.

4.0 Scaling Criteria

For laboratory studies to be meaningful to field situations, laboratory experiments must be dimensionally scalable. However, it is to be kept in mind that it is not possible scale all field factors to laboratory studies. Also, all scaling criteria may not be equally important for scaling purposes. Therefore, only important scaling criteria were considered for this study on the basis of inspectional and dimensional analyses:

Geometric Similarity

$$\left[\frac{L_x}{L_y}\right]_{\text{Model}} = \left[\frac{L_x}{L_y}\right]_{\text{Prototype}} \qquad (7)$$

Viscous Ratio

$$\left[\frac{\mu_o}{\mu_s}\right]_{\text{Model}} = \left[\frac{\mu_o}{\mu_s}\right]_{\text{Prototype}} \tag{8}$$

Ratio of Viscous to Gravity Forces

$$\left[\frac{L_x\, v\, \mu_o}{k\, g\, h\, \Delta\rho}\right]_{\text{Model}} = \left[\frac{L_x\, v\, \mu_o}{k\, g\, h\, \Delta\rho}\right]_{\text{Prototype}} \tag{9}$$

Longitudinal Dispersion Effects

$$\left[\frac{K_l}{L_x\, v}\right]_{\text{Model}} = \left[\frac{K_l}{L_x\, v}\right]_{\text{Prototype}} \tag{10}$$

Transverse Dispersion Effects

$$\left[\frac{K_t\, L_x}{v\, L_y^2}\right]_{\text{Model}} = \left[\frac{K_t\, L_x}{v\, L_y^2}\right]_{\text{Prototype}} \tag{11}$$

For the purpose of illustration, presented in Table 1 are the values of variables to show how the scaling criteria were met in this study between the model and prototype. Note that the oil used in this particular case is Tellus-320 and the solvent is iso-octane.

5.0 Experimental Apparatus, Materials and Procedure

5.1 Apparatus:

Schematic diagrams of the flow-visualization porous model and the experimental apparatus are given in Figures 2 and 3. The

flow-visualization model used in this study was comprised of a 1000cm^2 area of 1cm-thick porous pack sandwiched between two 5cm-thick plates. The lower plate, made of stainless steel, was designed to accommodate all necessary fittings including inlet and outlet ports and a filling plug for packing glass beads. The use of lower stainless-steel plate ensured higher strength of the model, a better access, and an unhindered flow-visualization process through the upper plate which was made of glass. The model was then mounted on to a robust stand which allowed for pivoting of the model at any desired angle. Prior to any displacement run in the model, it was pressure tested for strength and flexibility up to a maximum inlet pressures of 245 kPa. No significant deflection of the glass plate was noticed.

Two HPLC constant-rate pumps were used to inject the oil and the solvent into the porous pack. In the case of runs with slugs of graded-viscosity, the mixing between the oil and solvent was achieved by pumping the fluids through a long coiled-tubing and then through a mixing-filter. The produced fluid was collected at the outlet-end into sampling tubes by an automatic sampler at a fixed interval of time.

5.2 Porous Medium:

Class IVA-203 glass bead manufactured by Ferro Corporation was used as the porous medium model. Details of the dimensions of the porous pack and the relevant properties of the porous medium are furnished in Tables 2 and 3.

A tight and homogeneous packing in the model was achieved by positioning the model in an inclined position and then filling it

up with glass beads through the filling port (see Figure 2). During the process of packing, the model-assembly was mildly hammered to ensure a uniform distribution of glass beads in the model and a tighter pack.

5.3 Fluids:

In order to study the effects of viscosities, three different mineral oils -- Vitrea-22, Vitrea-150 and Tellus-320 -- were used in displacement runs as the "displaced fluid". Solvents, n-Octane and iso-Octane, were used as the "displacing fluid". Properties of these fluids are furnished in Table 4.

Prior to the start of displacements, correlations for densities and viscosities of the solvent-oil mixtures for each pair of fluids were established. Viscosity correlations presented in Figures 4-6 were used to design the graded slugs, and density correlations presented in Figures 7-9 were used to estimate the percent recovery of the individual fluids in the effluent.

For the set of displacement runs with slugs of linearly-graded viscosities, the upper and lower bounds for the length of the graded-viscosity region in the porous medium were estimated by using Equations 5 and 6 proposed by Coskuner and Bentsen. As can be noted from Table 5, for the horizontal system used in this study the upper and lower bounds were 11.93cm and 2.95cm, respectively. Thus, it was possible to accommodate and view the entire graded-region within the porous medium in the model.

A linear gradation in the viscosity of successive slugs was achieved by decreasing -- in equal steps -- the viscosity of slugs

at a regular interval. The design of the linear slugs used in these study are presented in Figures 10-12 for Vitrea-22, Vitrea-150 and Tellus-320, respectively. An interval of 0.05 pore volume of injection was chosen for all three oils and the displacements were carried out at 5mL/min. The viscosity-reduction steps chosen for these three oils were 5 mPa.s, 20 mPa.s and 50 mPa.s for Vitrea-22, Vitrea-150 and Tellus-320, respectively.

5.4 Homogeneity Test for the Porous Pack:

The homogeneity of the pack was tested by carrying out displacement tests using two equi-density and equi-viscosity fluids and then by monitoring the shape of the displacement front. During the displacement, a piston-like even front was encountered signifying the homogeneity of the porous pack (see Photograph 1).

5.5 Flow Visualization:

Flow visualization of the displacement process was achieved by the video recording and also by time-lapse photography during the displacement process. Visual images so captured were later utilized in the the data analysis.

5.6 Diffusion and Dispersion Effects:

Because the ratio of the finger width to the lateral dimensions a typical laboratory porous model is usually large, the effect of the transverse dispersion in such studies can be significant. In the field situation, however, transverse dispersion is much lower and therefore, its effect on viscous fingering should be considerably less significant than laboratory studies would seem to suggest (Stoneberger and Claridge, 1988). This aspect was taken into consideration in the design of the

experimental apparatus for studying the graded-viscosity zone concept.

In this study, diffusion effects were neglected because of higher flow rates were used, and only dispersion effects were considered. The following empirical equations of Perkins and Johnston (1963) were used to calculate transverse and longitudinal dispersions coefficients in the unconsolidated glass-bead pack used in our model.

$$K_l = D_o/F\phi + 0.5\ v\ \bar{d}\ \sigma_h \qquad (12)$$

$$K_t = D_o/F\phi + 0.0157\ v\ \bar{d}\ \sigma_h \qquad (13)$$

Neglecting the diffusion term, $D_o/F\phi$, dispersion coefficients, K_l and K_t, were estimated using the following equations:

$$K_l \cong 0.5\ v\ \bar{d}\ \sigma_h \qquad (14)$$

$$K_t \cong 0.0157\ v\ \bar{d}\ \sigma_h \qquad (15)$$

The average size of glass beads, $\bar{d}$, was 715 micron (0.0715 cm), and from the correlation provided by Perkins and Johnston, the inhomogeneity factor, σ_h, for glass beads used in this study was estimated at 5.0.

The values of K_l and K_t estimated at different displacement rates, v, are furnished in Table 6 and plotted in Figure 13. Notice that, even under laboratory conditions, transverse dispersion coefficients were much smaller compared to longitudinal dispersion coefficients. As a consequence, the effects of the

transverse dispersion could be neglected without introducing any serious errors into the analysis.

6.0 Experimental Results and Analysis

Table 7 summarizes the displacement runs conducted under various experimental conditions. In all, 37 displacement experiments were conducted, and 18 of these experiments were straight miscible displacements, i.e. without viscosity grading. Graded-viscosity slugs using Claridge's method were used in 15 runs; while 4 runs were conducted using slugs with linearly-graded viscosities.

Runs 1 and 2 were preliminary runs conducted to investigate the uniformity of the injection front, and the tightness and homogeneity of the porous pack. The problem of preferential injection at the injection end was encountered. This problem was rectified by altering and manipulating the lengths of injection manifolds at the inlet end, and a homogeneity test was conducted by carrying out a displacement of an oil by an identical, equi-viscous colored oil. An even front, as shown in Photograph 1 in Plate 1, was noticed signifying a uniform injection front and the homogeneity of the pack.

As is evident from Table 7, several repeat runs, such as: Runs 4, 14, 15, 17, 36 and 37 were conduced to verify, at random, the repeatability of experimental results and to ensure the quality of experimental data.

Analyses carried out were both qualitative and quantitative in nature. In the qualitative analysis, observations made during

the flow-visualization process were studied; while in the quantitative analysis, the quantitative aspects, such as net and cumulative oil recoveries were monitored and studied.

6.1 Qualitative Analysis:

Presented in Photographs 2-6 in are visual images of viscous fingers captured in a miscible displacement run, Run 17, at different stages in the run. In this run, the displaced fluid was Tellus-320 oil (μ_o = 717.2 mPa.s) and the displacing fluid was iso-octane. The displacement was conducted at a flow rate of 10mL/min. Notice that viscous fingers initiated in an even manner across the entire the width of the porous pack soon after the injection of the solvent began. However, as the fingers grew with time, one single finger appeared to be emerging as the most dominating finger. The dominating finger, by the process of continuous tip-splitting at the tip and the resulting formation of dendritic patterns, linked the neighboring fingers as it was on its way towards the outlet-end. Eventually, most fingers became interlinked or cross-linked with one another, and as a consequence, an improvement in the sweep resulted. The manner in which the viscosity ratio between the displaced and displacing fluids affects the formation, growth and propagation of viscous fingers can be illustrated by comparing Photograph 4 with Photograph 7. Photograph 7 was taken during a miscible displacement of Vitrea-22 (μ_o = 41.7 mPa.s) conducted at an identical flow rate of 10mL/min. Furthermore, both Photographs 4 and 7, were taken after 230 seconds of the displacement process. It is evident from these two photographs that a decrease in the viscosity ratio

reduced the width and number of viscous fingers and resulted in a better sweep. Also, it was quite obvious that the dendritic patterns which contributed towards the entrapment of immobile oil are much less prominent when the viscosity ratio between the displaced and the displacing fluids was lower. Likewise, all miscible displacement runs exhibited a similar fingering behavior and pattern. However, it was also observed that intensity of tip-splitting and complexities in the dendritic patterns were also influenced by the displacement flow rate. At higher flow rates, such behavior was more prominent.

In displacements by graded-viscosity slugs, the fingering of the displacing fluid decreased very significantly. This may be attributed to the existence of much more favorable viscosity ratios between the successive slugs due to viscosity gradation. Colored oil was used in the slug to make the visual analysis of the process easier, and to make concentration-contrasts between successive slugs more obvious. Photographs 8 and 9 depict such contrast for Run 23. Note here that this run was conducted using linearly graded slugs of Vitrea-22 and iso-octane, and the displacement was carried out at a flow rate of 5mL/min. Each successive slug in this photograph is depicted by a unique streak of different, but of diminishing color intensity. In other words, the concentration of the oil component in the slug was continuously reduced. A near total sweep was exhibited in this run towards the end of the experiment (see Photograph 9).

In the displacements with linearly graded slugs using Coskuner and Bentsen's approach, it was observed that effects of

viscous instabilities were much lesser than those observed in displacements with graded-viscosity slugs. As evident from Photograph 10 taken during Run 30 (displacement rate = 5mL/min), a near piston-like front developed between each successive slugs because of linear gradation of viscosities between the successive slugs.

6.2 Quantitative Analysis:

6.2.1 Miscible Displacement Runs:

As indicated in Table 6, miscible displacement runs were conducted using three different oils and at 5 different flow rates. Presented in Figures 14-16 are the cumulative oil recoveries as a function of displacement rates for Vitrea-22, Vitrea-150 and Tellus-320 oils. As expected, in all cases, cumulative oil recoveries increased as the displacement rates were decreased because at lower displacement rates, the extent of viscous instabilities were also lower. Similar effects also became evident when cumulative oil recoveries were plotted as a function of viscosity ratios between the displaced oil and displacing solvent (see Figures 17-20).

6.2.2 Displacements Using Graded-Viscosity Slugs:

As it was mentioned earlier, two set of runs using graded-viscosity slugs were conducted -- one using the method proposed by Claridge (1978), the other using the method proposed by Coskuner and Bentsen (1987).

Oil and solvent were pre-mixed in the designed proportions prior to its entry into the porous medium to achieve a viscosity gradation between the oil and the displacing slugs. Because the

oil was used as a component in displacing slugs, the net cumulative oil recovered was estimated by subtracting the cumulative volume of oil injected with the slugs.

6.2.2.1 Graded-Viscosity Slugs -- Claridge's Method:

Presented in Figures 21-23 are net cumulative oil recovered as a function of the displacement rates for Vitrea-22, Vitrea-150 and Tellus-320, respectively, for displacements using Claridge's Method. In all cases, it was observed that initial net oil recovered was very low, although it appeared to increase gradually with the injection of several pore volumes of the slugs. Also, as evident from these figures, the actual impact of graded-slugs on oil recovery became apparent only after several pore volumes of slugs were injected into the system. Trends of curves in these figures suggest that if the injections of slugs were continued sufficiently long enough, a much better oil recovery would have resulted. Similar observations and trends also became obvious when net cumulative oil recoveries were plotted as a function of viscosities of the displaced oil (see Figures 21-24).

6.2.2.2 Linearly Graded Slugs -- Coskuner and Bentsen Approach:

Three displacement runs using linearly graded slugs were conducted at a displacement flow rate of 5 mL/min and the net oil recovery was plotted as a function of the displaced oil viscosity (see Figure 28). Here too, the trend in the oil recovery curves were as expected -- the higher the displaced oil viscosity lower was the net recovery of the oil. Furthermore, as it is evident from Figures 29 and 31 that for the same flow rate and oil viscosity, linear gradation of slug viscosity using Coskuner and

Bentsen's theory yielded much higher net oil recoveries than the gradation of slugs using Claridge's method for Vitrea-22 and Tellus-320 oils. Although such observation was not obvious for Vitrea-150 oil (see Figure 30), it is to be noted that the displacement run in this case was discontinued very early -- presumably much before the effects began to manifest.

However, in spite of significant improvements in the net oil recovery towards the end of the experiments, overall net oil recoveries still remained lower compared to those in miscible displacements with pure solvent within our experimental range. In all cases, however, it became quite obvious that if the displacements with linearly graded slugs were continued further, it could have been possible that the net oil recovery by linearly graded slugs would have surpassed the net oil recovery obtained by miscible displacement with pure solvent. But whether such continued injection of linearly graded slugs for marginally higher net recovery would be economic is the major consideration that one has to take into account.

7.0 Economic Viability

Results of this study indicate that although the use of graded-viscosity slugs minimized the extent of viscous instabilities significantly, the enhancement in the net oil recovery was very marginal. Therefore, one needs to be cautiously optimistic about the application of such a method in field situations because, for a displacement process to be successful in the field application, it has to be economically viable.

The cost of production of a single barrel of heavy oil is

much higher than that of a barrel of lighter conventional oil. Hence, it seems quite unattractive under the present circumstances of low oil prices to pump in the oil produced at a higher cost back into the formation when the anticipated net increase in oil recovery is only very marginal. Therefore, unless cheaper and more viscous solvents are available for use in slugs, this method would appear to serve a self-defeating goal.

Because viscosity-graded slugs minimize the extent of viscous instability significantly, they may, however, have some useful applications in reservoirs with severe problems of viscous instabilities.

Based on the experimental data gathered in this study, a hypothetical economic analysis was conducted. In this analysis, it was assumed that the propane at the current price of $54.77 per cubic metre would be used as the solvent, and the price of oil would remain at $125.79 per cubic metre ($20.00/barrel).

Presented in Tables 8 and 9 are return-ratios on costs of the solvent used after 1 and 2 pore volumes of injection for all three displacement processes considered in this study. In presenting this illustrative case, data from Runs 23, 28 and 30 (Oil = Vitrea-22; flow rate = 5mL/min)were used. As can be noted from Table 8, the continuous viscosity gradation by the use of linear-slugs yielded a higher return on the cost of solvent used. However, this cost advantage gradually diminished as the displacement was continued further, and eventually, the cost of the solvent exceeded the oil-revenue (see Table 9). Therefore, it appears that the only possible way to reap economic benefits from

the use of continuously graded linear-slug is to follow the solvent-slugs with some cheaper fluids, such as water.

Tables 8 and 9 also indicate that the economic benefits and efficiency of a miscible displacement process are more pronounced in the earlier stages in the flooding processes. However, regardless of length of the flooding process, use of graded-viscosity slugs appeared to be least economic.

8.0 Summary and Conclusions

An experimental set-up that facilitated flow visualization studies in a scaled rectangular porous medium was designed, built, and successfully tested through a series of displacement runs using pure solvent and viscosity-graded slugs of solvent and oil.

Based on the experimental results and analysis presented herein, and keeping in mind that these results may apply only to the particular sand-fluid system modeled in this study, following conclusions may be drawn:

1. The flow-visualization study helped develop a qualitative and quantitative understanding of displacement processes, particularly, with regard to the formation and propagation of viscous fingers.
2. Effects of viscosity gradation on the extent of viscous instabilities were studied. It was observed that the extent of viscous instabilities diminished significantly when slugs with graded viscosities were used to displace the oil.
3. Based on cumulative oil recovery data, the use of slugs with linearly-graded viscosities appeared to be more effective than the use of graded slugs designed as per Claridge's method.
4. In spite of their effectiveness in diminishing the extent of viscous instabilities, the use of graded-viscosity bank can become economically attractive only if a cheaper and more viscous solvent became available. Otherwise, injection of the produced crude oil as one of the components of viscous slugs becomes a self-defeating goal.

9.0 Recommendation for Future Work

This study helped us obtain a useful insight into the mechanisms in miscible-displacement processes under different experimental conditions. The visual model constructed for this study had appears to be an effective, convenient and robust tool to facilitate flow visualization studies. Therefore, it is recommended that this model and the experimental set-up be utilized for further studies to investigate displacement mechanisms in miscible and immiscible displacement processes. As Homsy (1987) has quite justifiably pointed out that our understanding of displacement processes in immiscible and miscible displacements is rather limited and far from being complete despite numerous work reported in the literature.

Acknowledgement

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Nomenclature

c	solvent concentration
$\bar{d}$	average glass bead size
D_o	molecular diffusion coefficient
E	effective viscosity ratio
F	formation resistivity factor
g	acceleration due to gravity
H	homogeneity factor
k	absolute permeability
L_x	width of the porous medium
L_y	thickness of the porous medium
K	Koval's factor
K_l	longitudinal dispersion coefficient
K_t	transverse dispersion coefficient
M	mobility ratio
v	darcy velocity
V	viscosity ratio of pure fluids
V_{pv}	pore volume of graded bank
V_{slug}	pore volume of slug
Z	length of the porous medium
μ_o	viscosity of oil
μ_s	viscosity of solvent
$\Delta\rho$	density-difference between the oil and solvent
σ_h	inhomogeneity factor
ϕ	porosity

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Table 1: Scaling Parameters of the Model and Prototype for Tellus-320 Oil

Parameters	Prototype	Model
L_x (m)	150.0	0.50
L_y (m)	60.0	0.20
h (m)	3.0	0.01
(μ_o/μ_s)	1398.0	1398.0
k (μm^2)	3.0	159.0
v (m/day)	0.1	3.6
K_l (m^2/s)	1.63E-6	1.96E-7
K_t (m^2/s)	5.14E-8	6.17E-9

Table 2: Dimensions of the Porous Pack

Length (m)	0.50
Width (m)	0.20
Thickness (m)	0.01

Table 3: Properties of the porous medium

Type	Class IV Glass Beads (Ferro Corporation)
Size Range	840-590 Micron
Average Size	715 Micron
Porosity	0.379
Absolute Permeability	159.0 darcies

Table 4: Fluid properties at the room temperature, 23°C

Fluids	Density [kg/m^3]	Viscosity [mPa.s]
VITREA-22	857.4	41.694
VITREA-150	879.7	419.0
TELLUS-320	885.1	717.24
n-Octane	700.6	0.515
iso-Octane	691.0	0.513

Table 5: Bounds for the Length of Graded Region (ΔZ)

Displaced Oil	ΔZ - Upper Bound (cm)	ΔZ - Lower Bound (cm)
Vitrea-22	11.789	2.947
Vitrea-150	11.920	2.980
Tellus-320	11.926	2.982

Table 6: Longitudinal and transverse dispersion coefficients

Flow Rate [mL/min]	Velocity [cm/s]	K_l [cm^2/s]	K_t [cm^2/s]
2.0	0.004398	7.86E-4	2.47E-8
4.0	0.008795	1.57E-3	4.94E-5
5.0	0.01099	1.96E-3	6.17E-5
8.0	0.01759	3.14E-3	9.87E-5
10.0	0.02199	3.93E-3	1.23E-4

Table 7: Summary of Displacement Runs

Flow rate (mL/min)	Category	VITREA-22	VITREA-150	TELLUS-320
2.0	Miscible	Run 22	Run 10	Runs 21 & 36
	Graded-Slug	Run 29	Run 11	Run 34
4.0	Miscible		Run 7	
	Graded-Slug		Run 8	
5.0	Miscible	Run 23	Runs 3 & 37 (Trial Run 2)	Run 20
	Graded-Slug	Run 28	Runs 4 & 5	Run 33
	Linear-Slug	Run 30	Runs 15 & 16	Run 35
8.0	Miscible	Run 24	Run 12	Run 19
	Graded-Slug	Run 26	Run 13	Run 32
10.0	Miscible	Run 25	Run 6 (Trial Run 1)	Runs 17 & 18
	Graded-Slug	Run 27	Runs 9 & 14	Run 31

Table 8: Cost Return Ratio of the Oil Recovery to the Solvent Used at 1 Pore Volume of Displacing Slug Injection.

Process	Net Oil Recovery (pv)	Solvent Content (pv)	Oil Revenue ($)	Solvent Cost ($)	Ratio = $\frac{\text{Oil Revenue}}{\text{Solvent Cost}}$
Miscible	0.53	1.00	66.67	54.77	1.22
Graded-Slug	0.05	0.14	6.29	7.67	0.82
Linear-Slug	0.45	0.63	56.60	34.50	1.64

Table 9: Cost Return Ratio of the Oil Recovery to the Solvent Used at 2 Pore Volumes of Displacing Slug Injection.

Process	Net Oil Recovery (pv)	Solvent Content (pv)	Oil Revenue ($)	Solvent Cost ($)	Ratio = $\frac{\text{Oil Revenue}}{\text{Solvent Cost}}$
Miscible	0.73	2.00	91.83	109.54	0.84
Graded-Slug	0.35	1.11	44.03	60.79	0.72
Linear-Slug	0.69	1.63	86.79	89.27	0.97

Figure 1: Design of Graded Slugs Using Claridge's Method

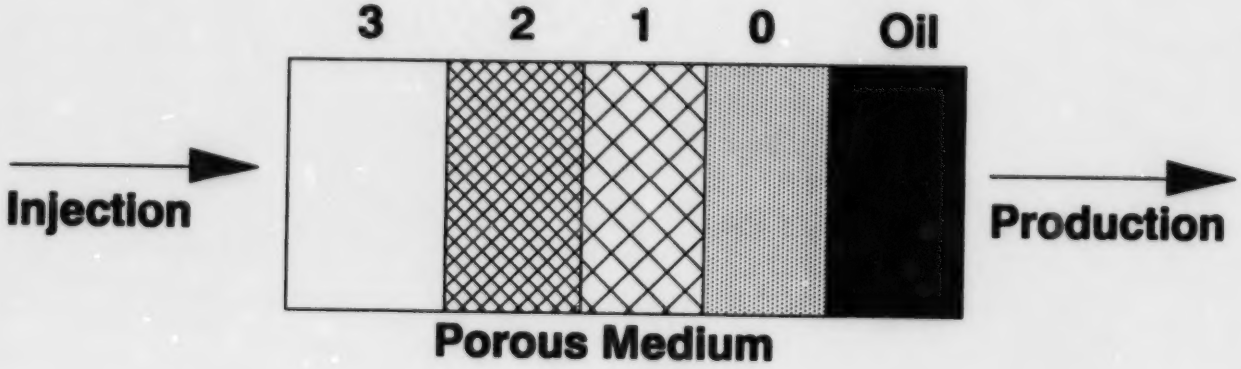


Figure 2 : Schematic Diagram of the Flow Visualisation Model

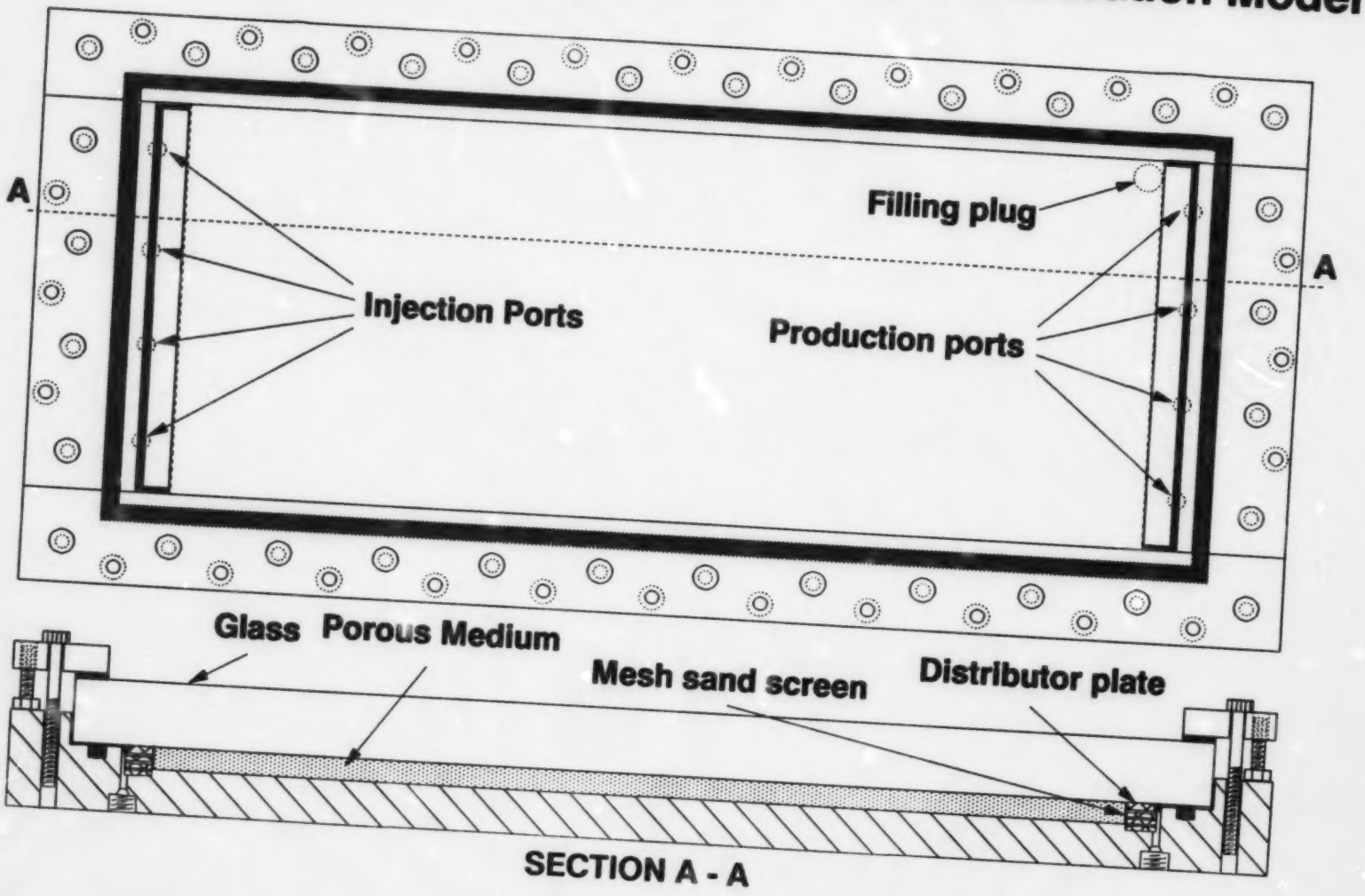


Figure 3 : Schematic Diagram of the Experimental Apparatus

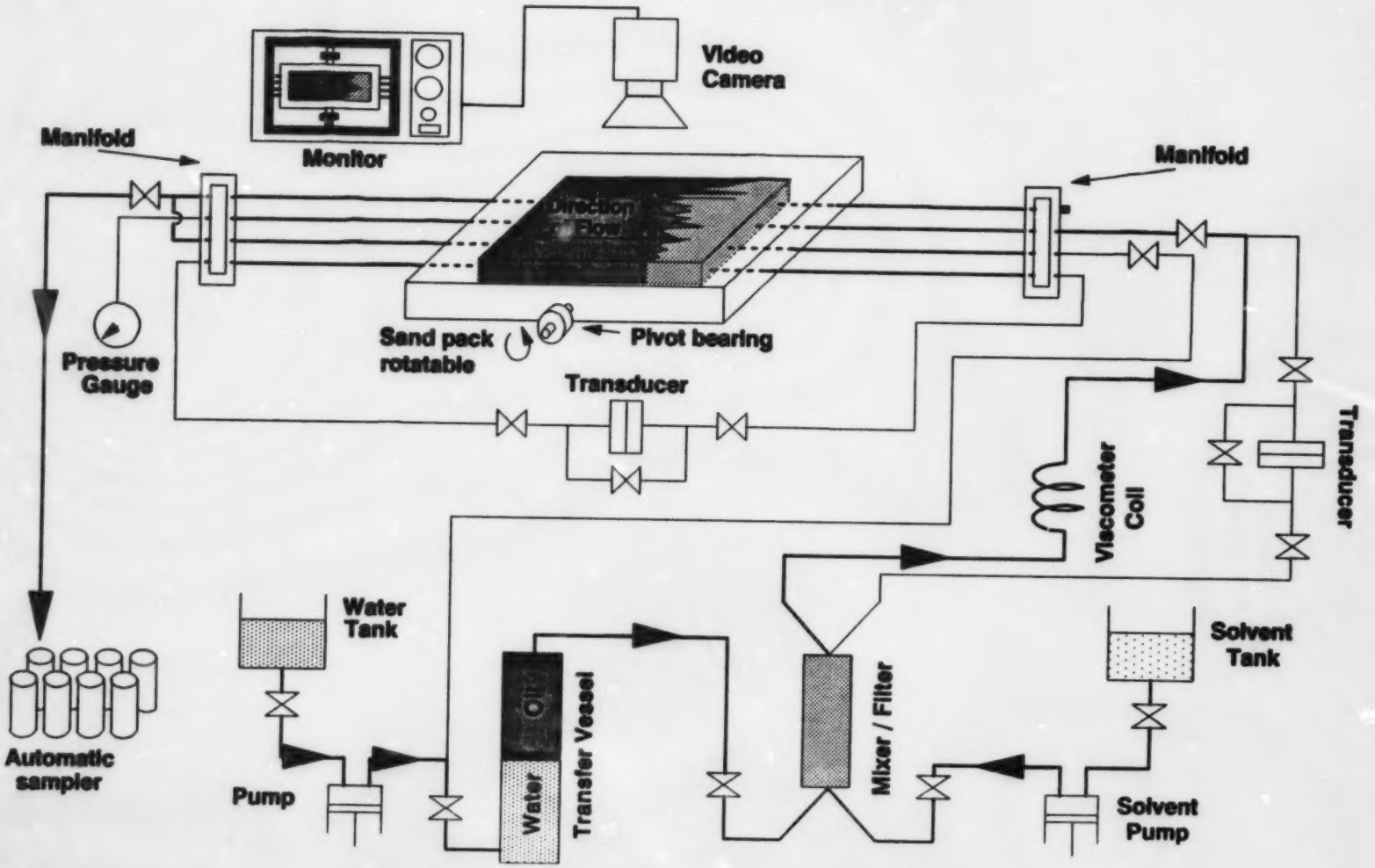


Figure 4: Density Correlation for the Mixture of Vitrea-22 and iso-Octane

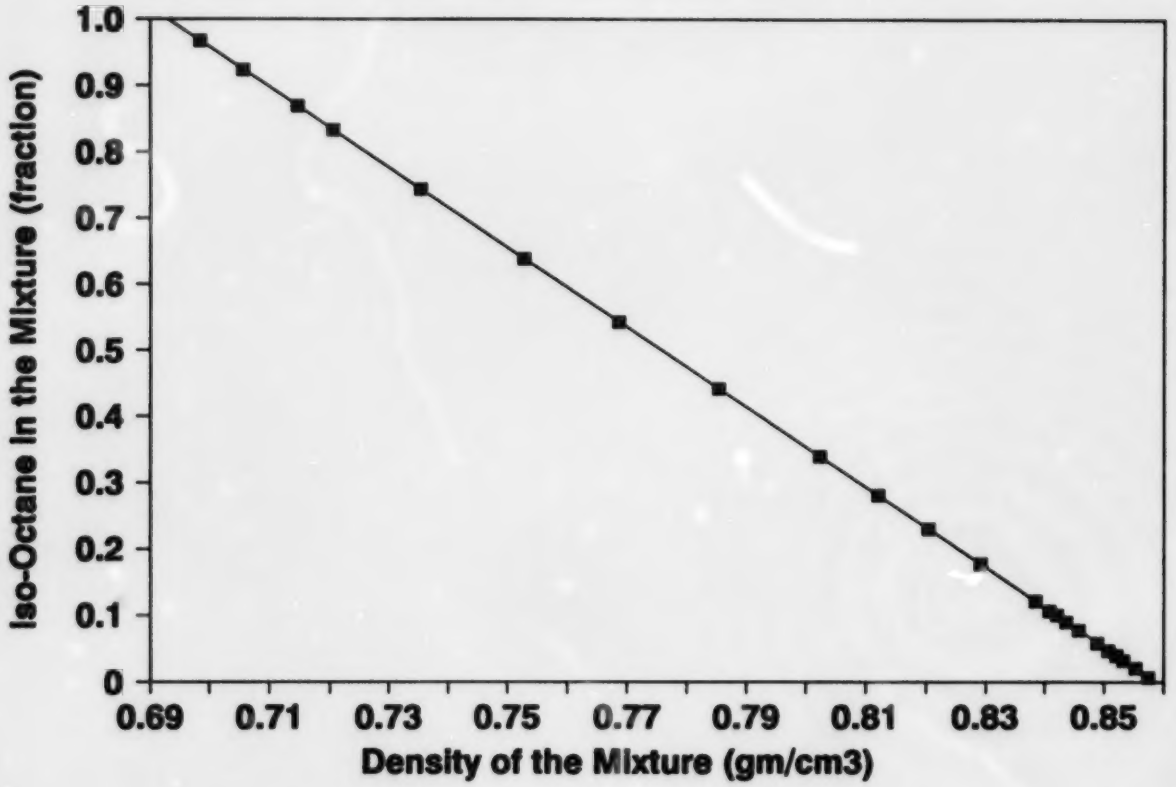


Figure 5: Density Correlation for the Mixture of Vitrea-150 and n-Octane

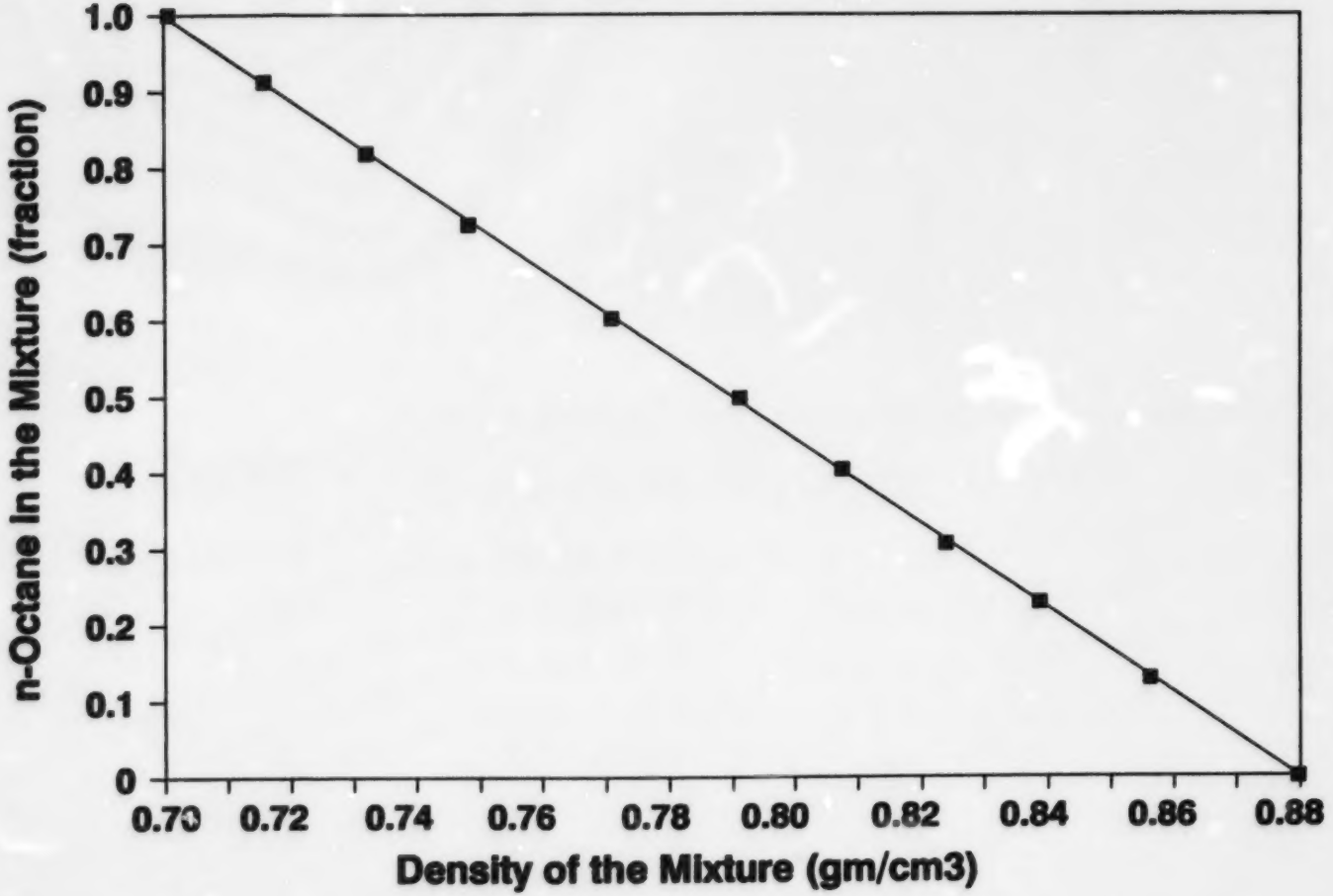


Figure 6: Density Correlation for the Mixture of Tellus-320 and iso-Octane

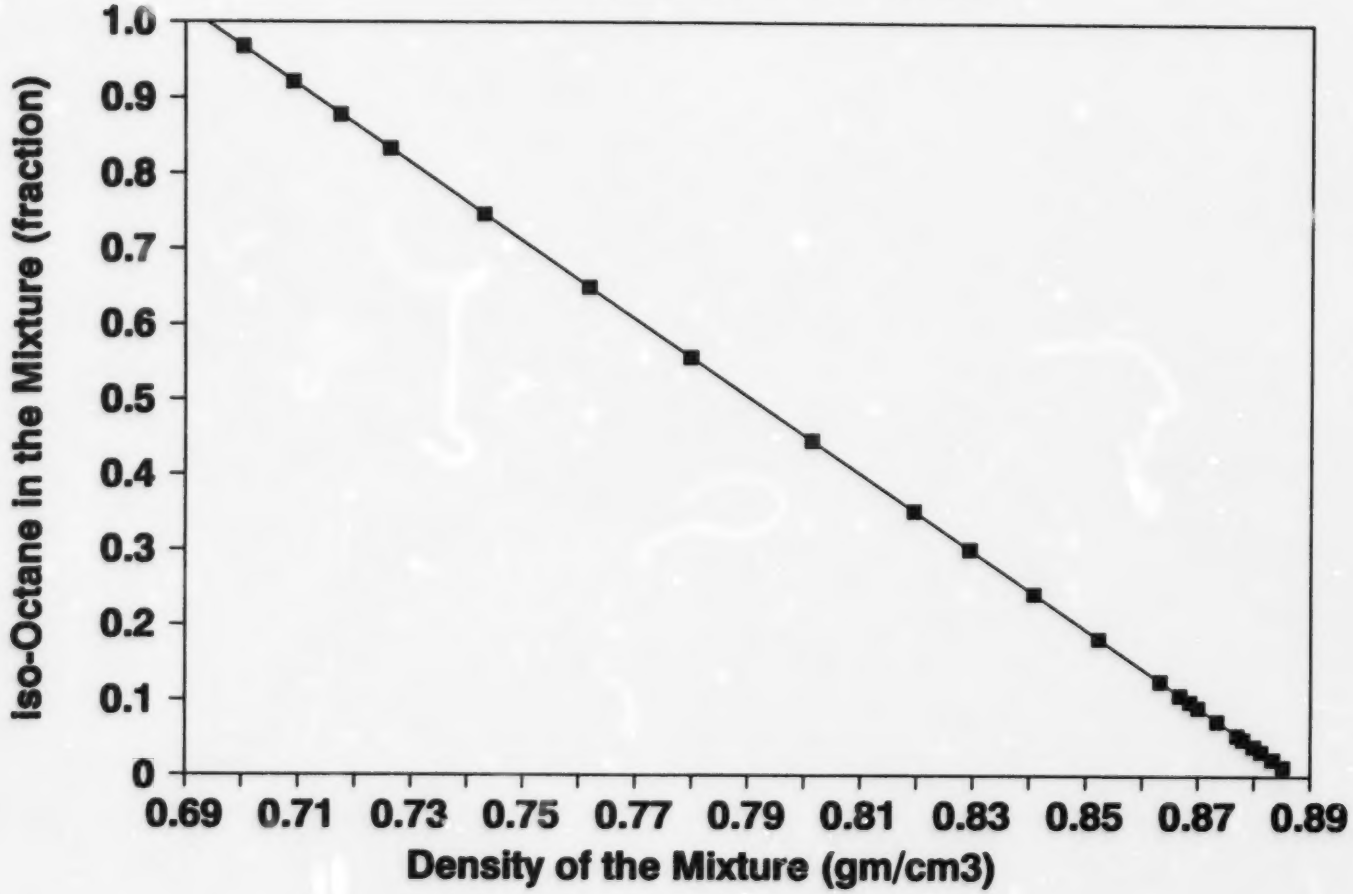


Figure 7: Viscosity Correlation for the Mixture of Vitrea-22 and iso-Ocatne

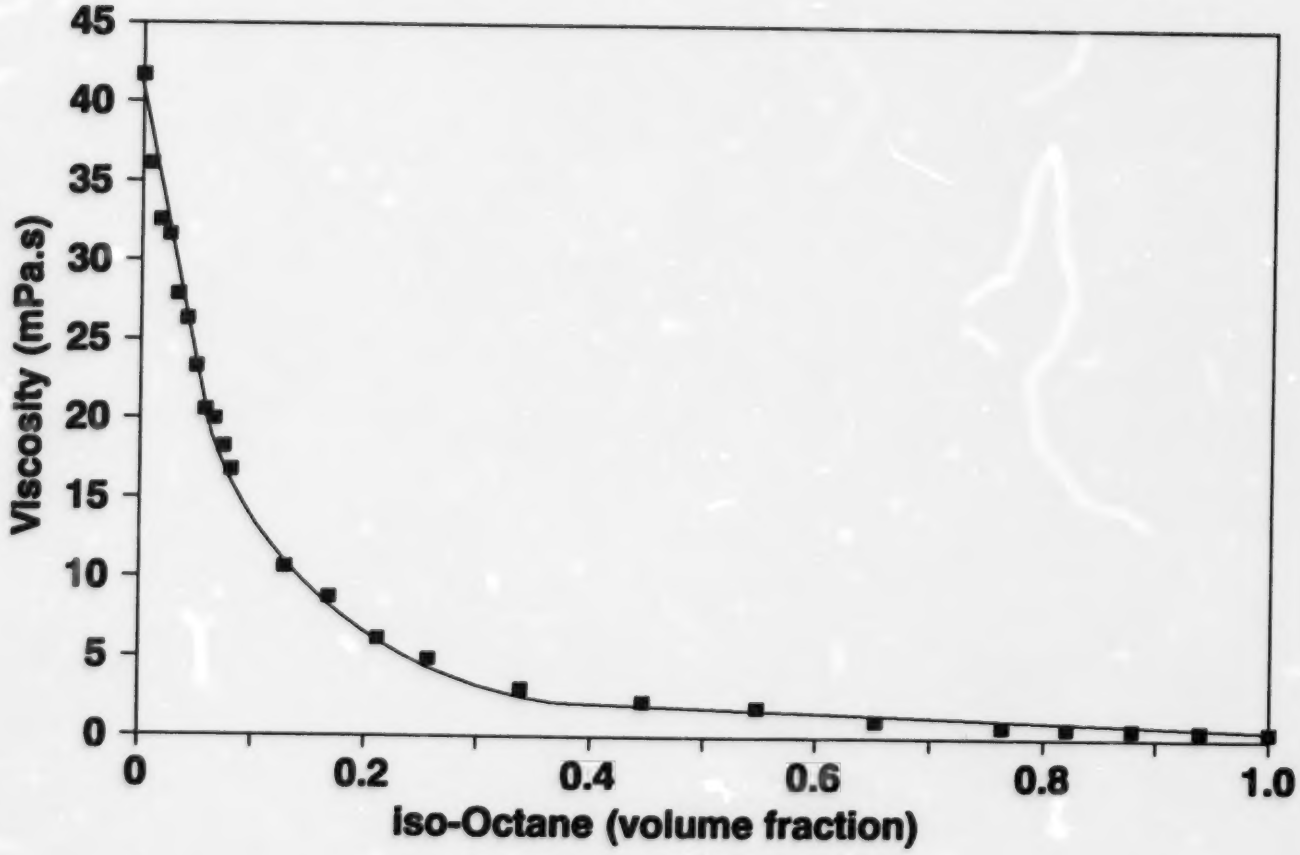


Figure 8: Viscosity Correlation for the Mixture of Vitrea-150 and n-Octane

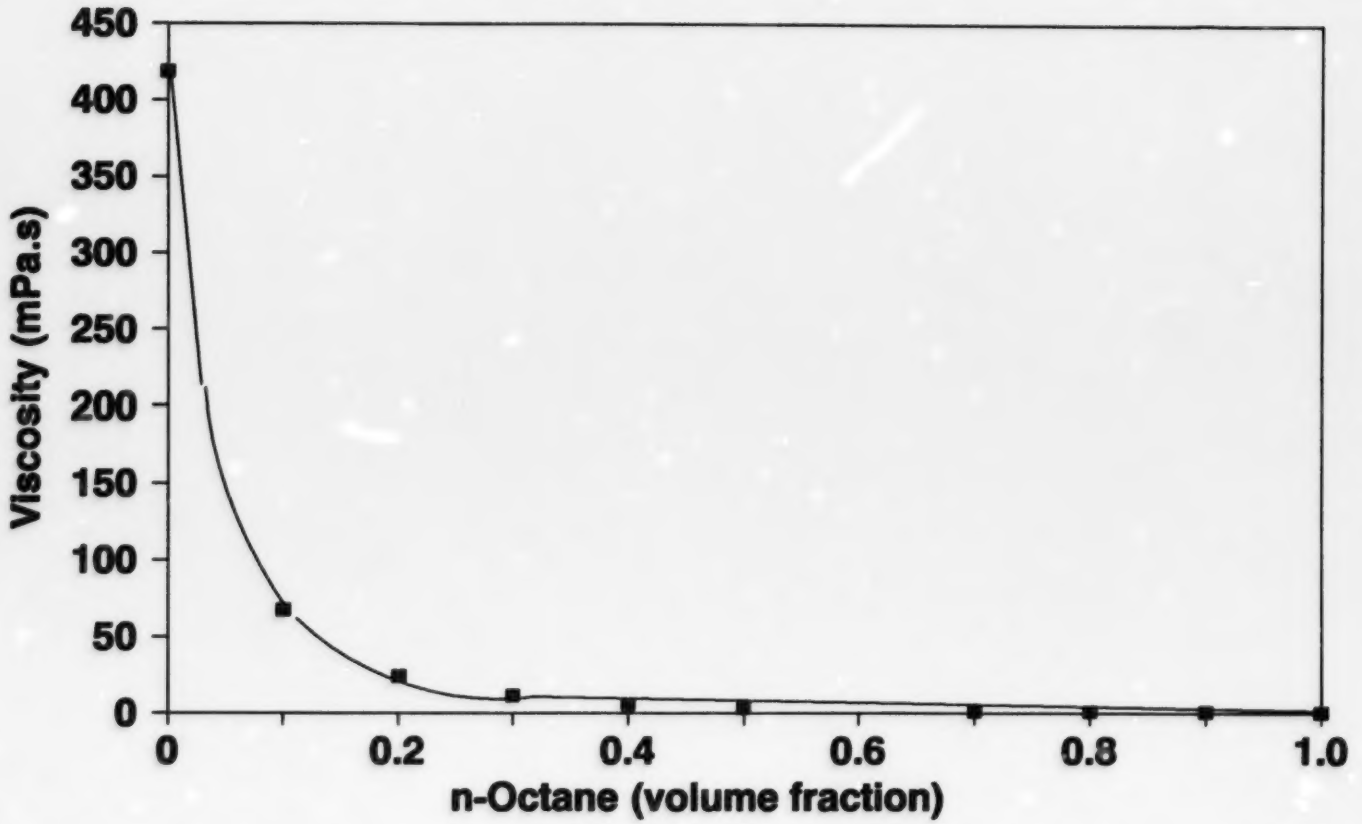


Figure 9: Viscosity Correlation for the Mixture of Tellus-320 and iso-Octane

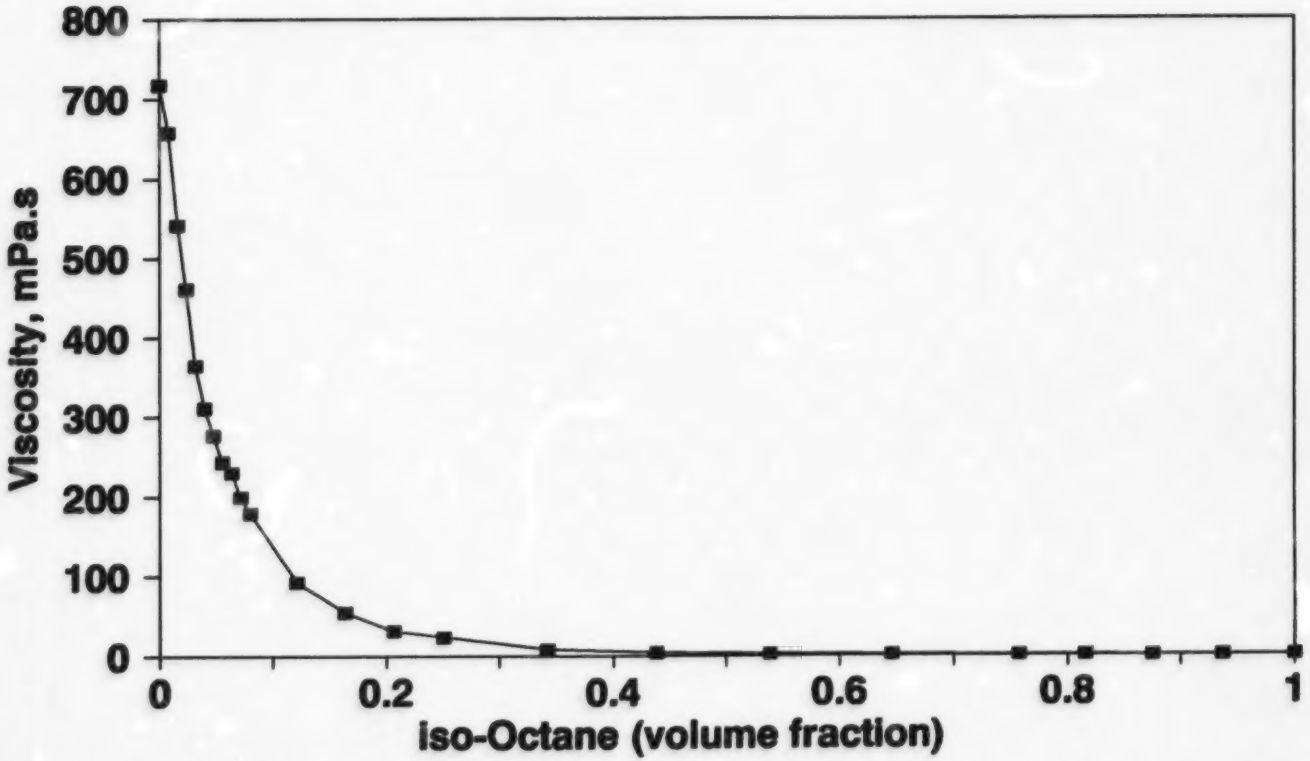


Figure 10: Design of Linearly Graded Slugs Using Vitrea-22 and iso-Octane

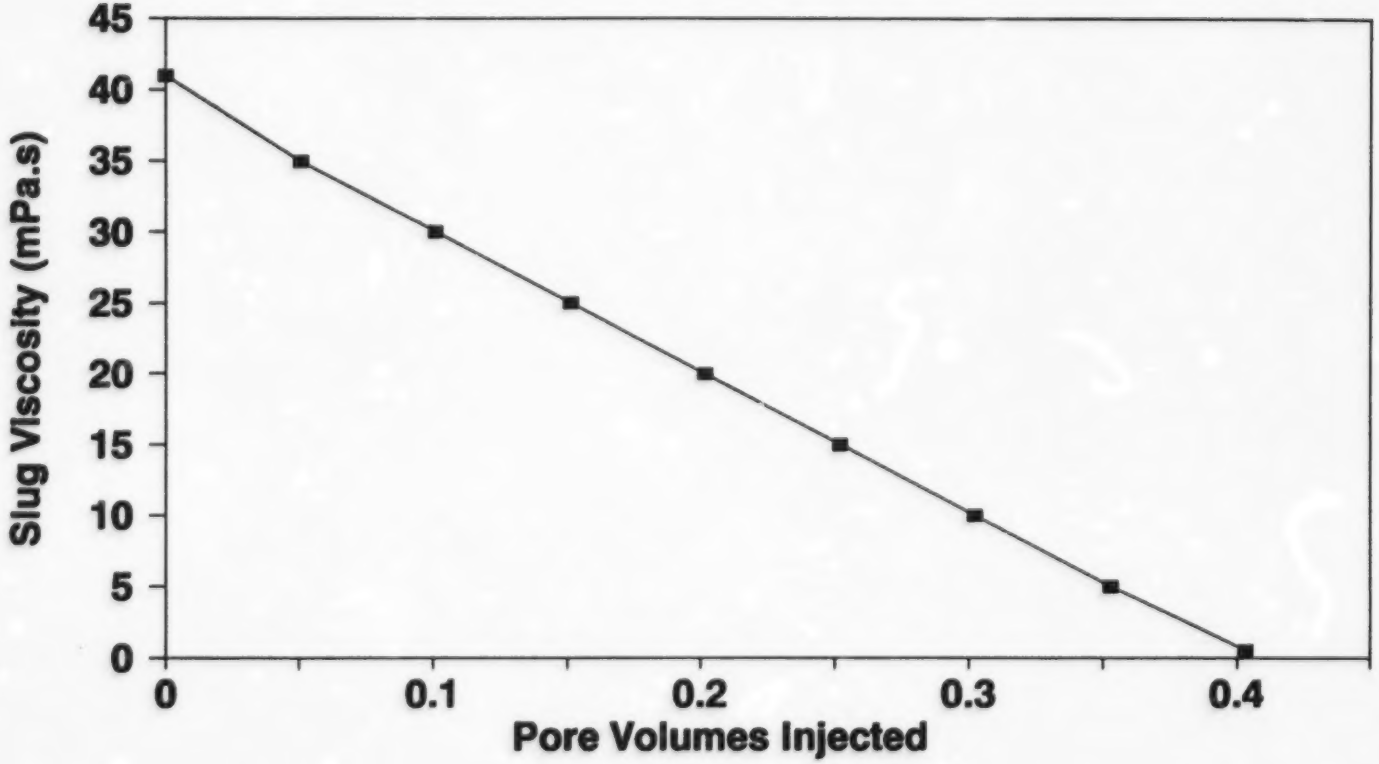


Figure 11: Design of Linearly Graded Slugs Using Vitrea-150 and n-Octane

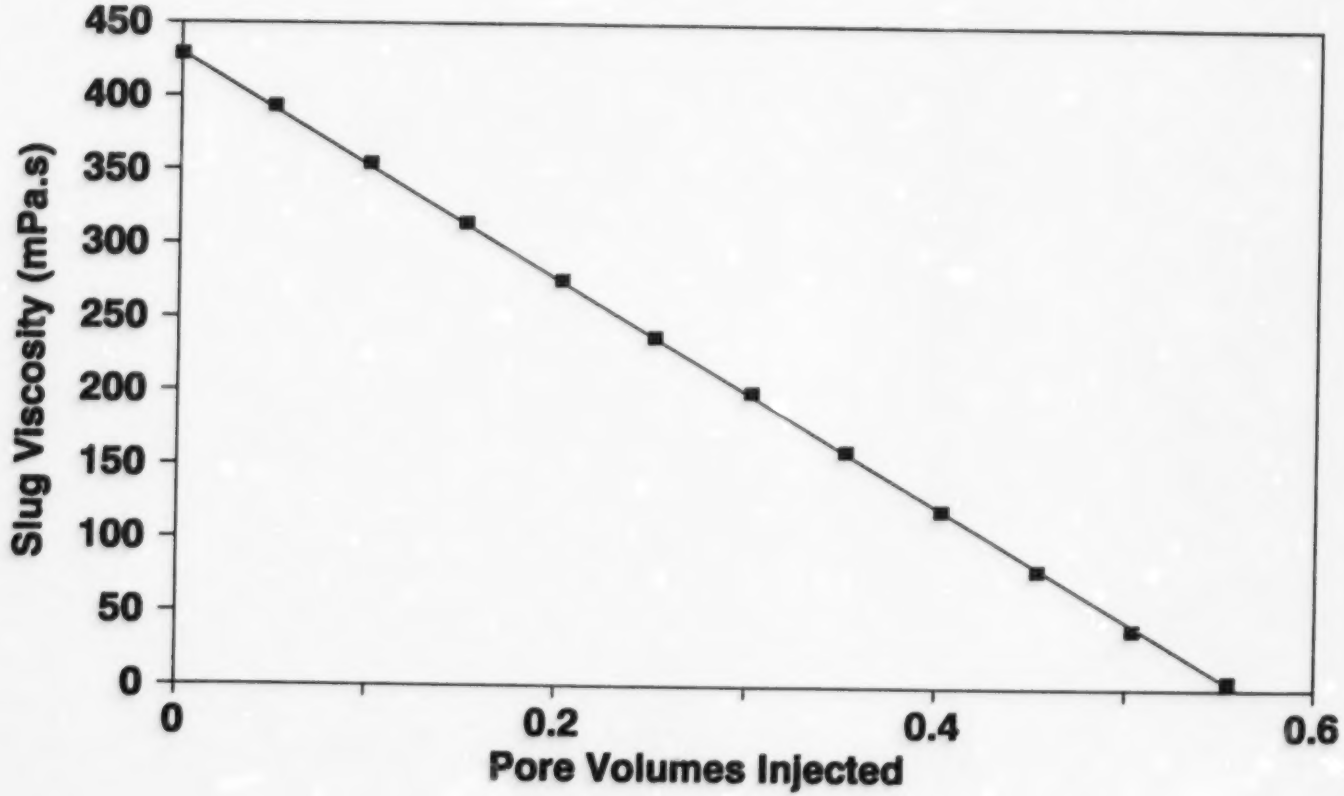


Figure 12: Design of Linearly Graded Slugs Using Tellus-320 and iso-Octane

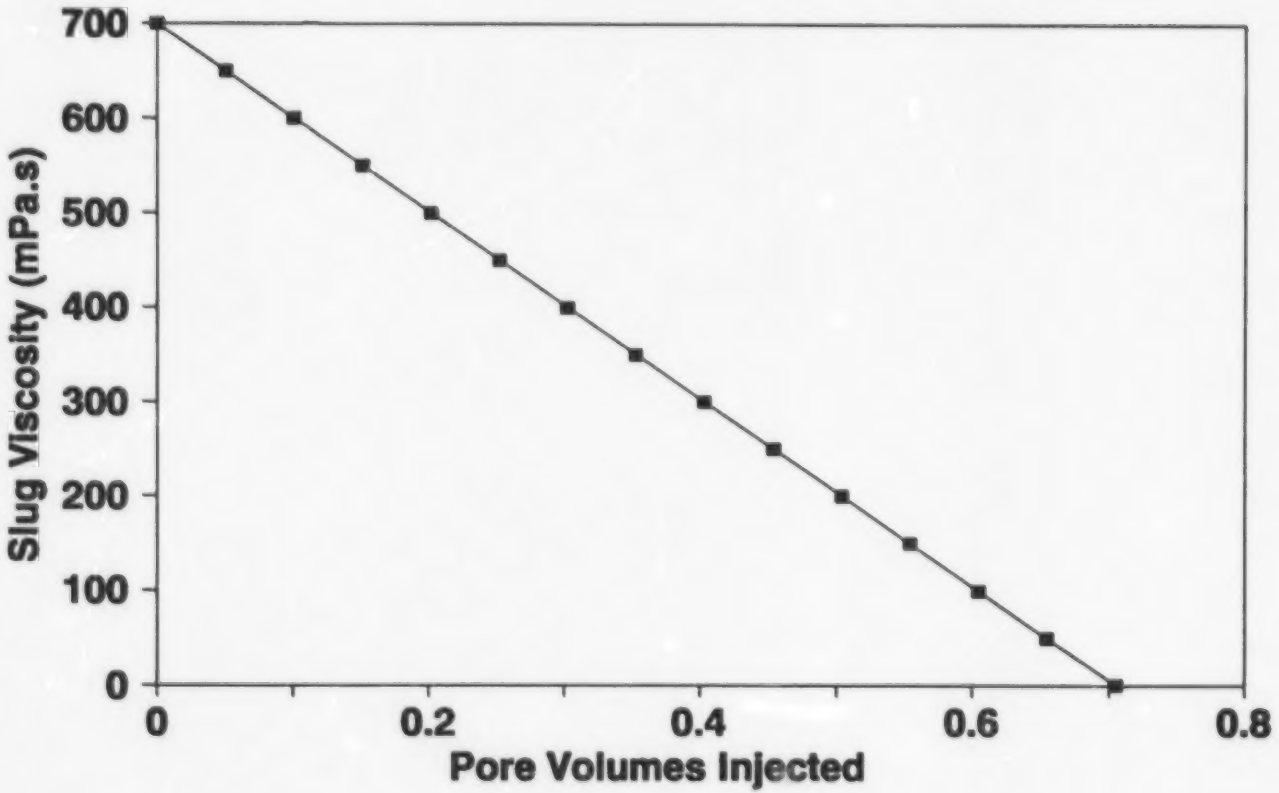


Figure 13: Dispersion Coefficient as a Function of Displacement Rate

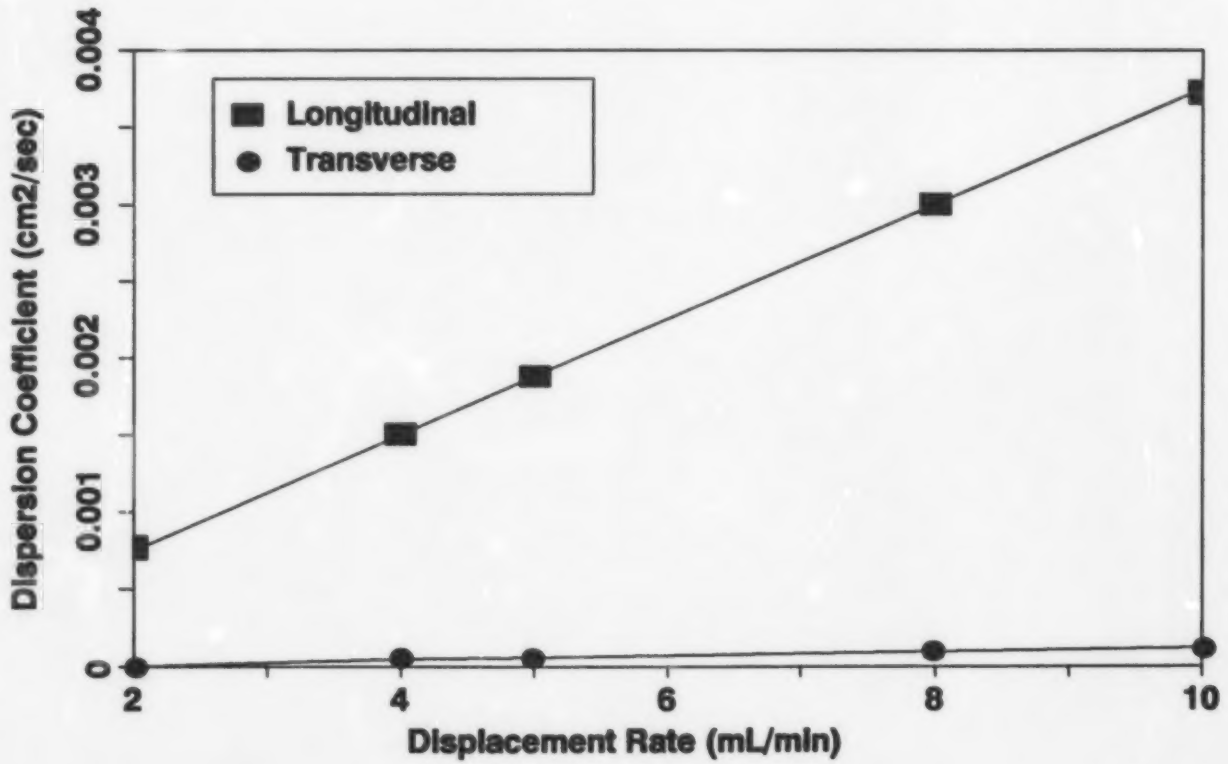


Figure 14: Effects of Displacement Rate on Cumulative Oil Recovery
(Miscible Displacement for Vitrea–22 Oil)

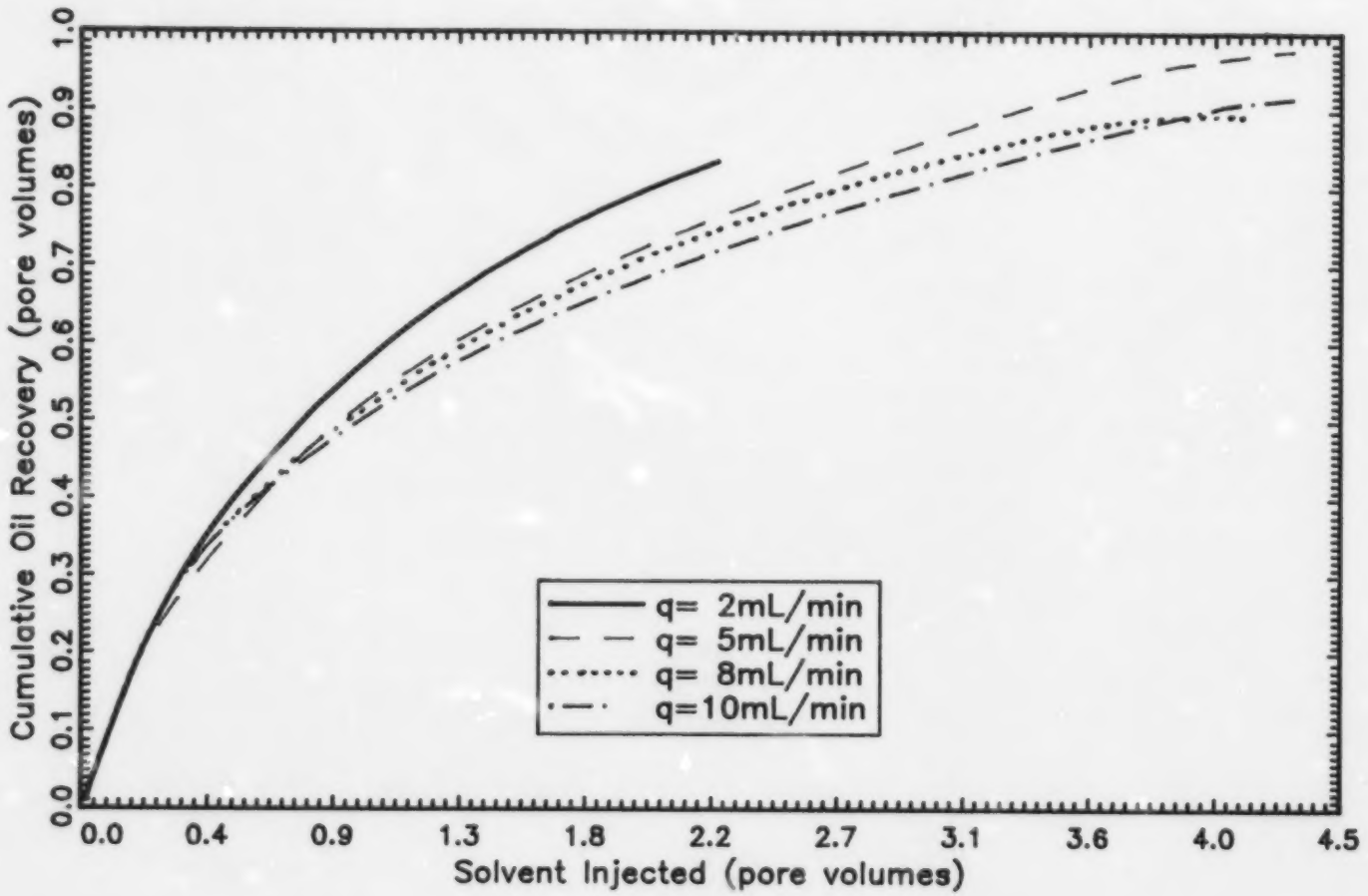


Figure 15: Effects of Displacement Rate on Cumulative Oil Recovery
(Miscible Displacement for Vitrea–150 Oil)

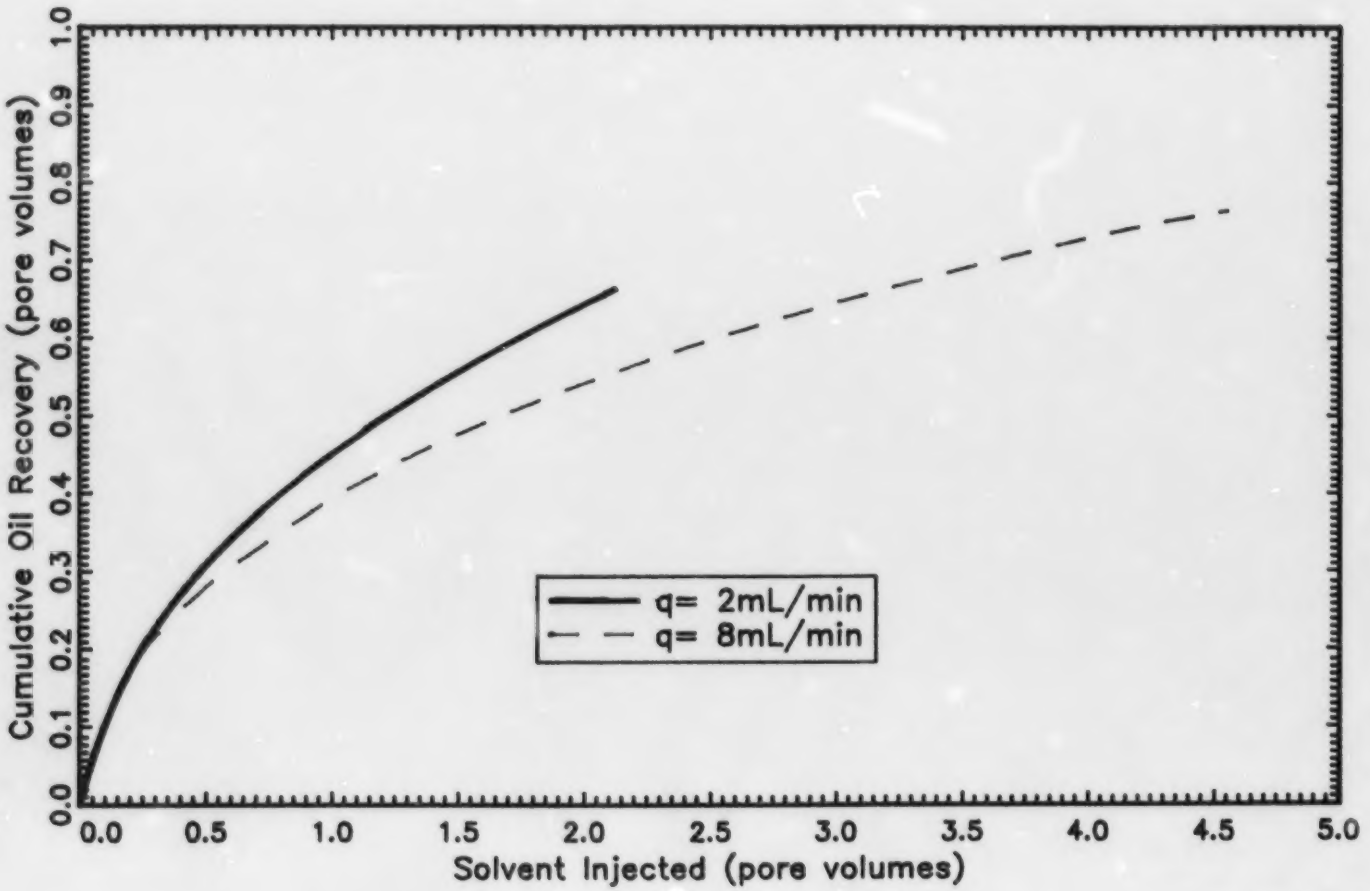


Figure 16: Effects of Displacement Rate on Cumulative Oil Recovery
(Miscible Displacement for Tellus–320 Oil)

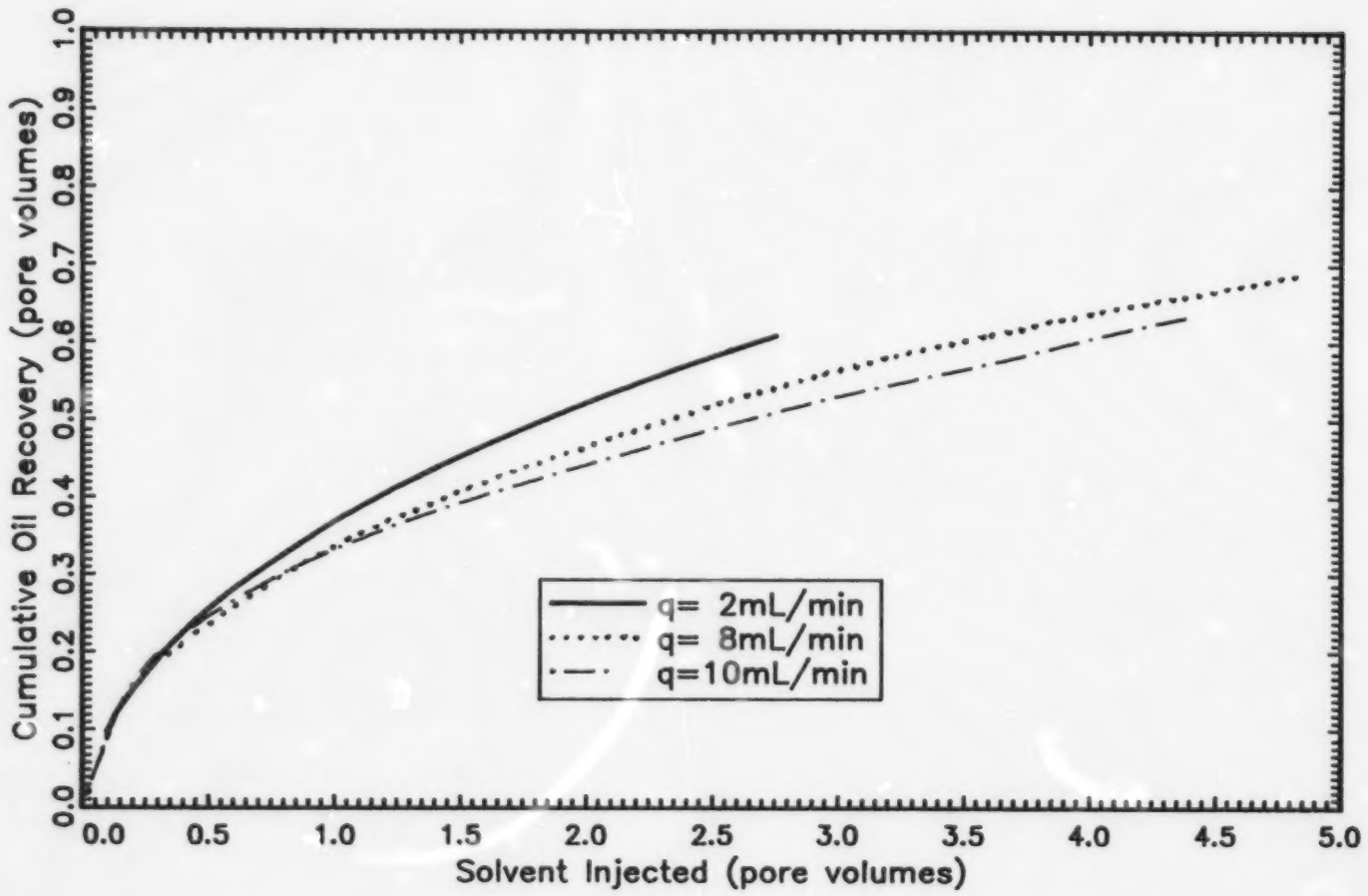


Figure 17: Effect of Viscosity Ratio on Cumulative Oil Recovery
(Miscible Displacement at q = 2mL/min)

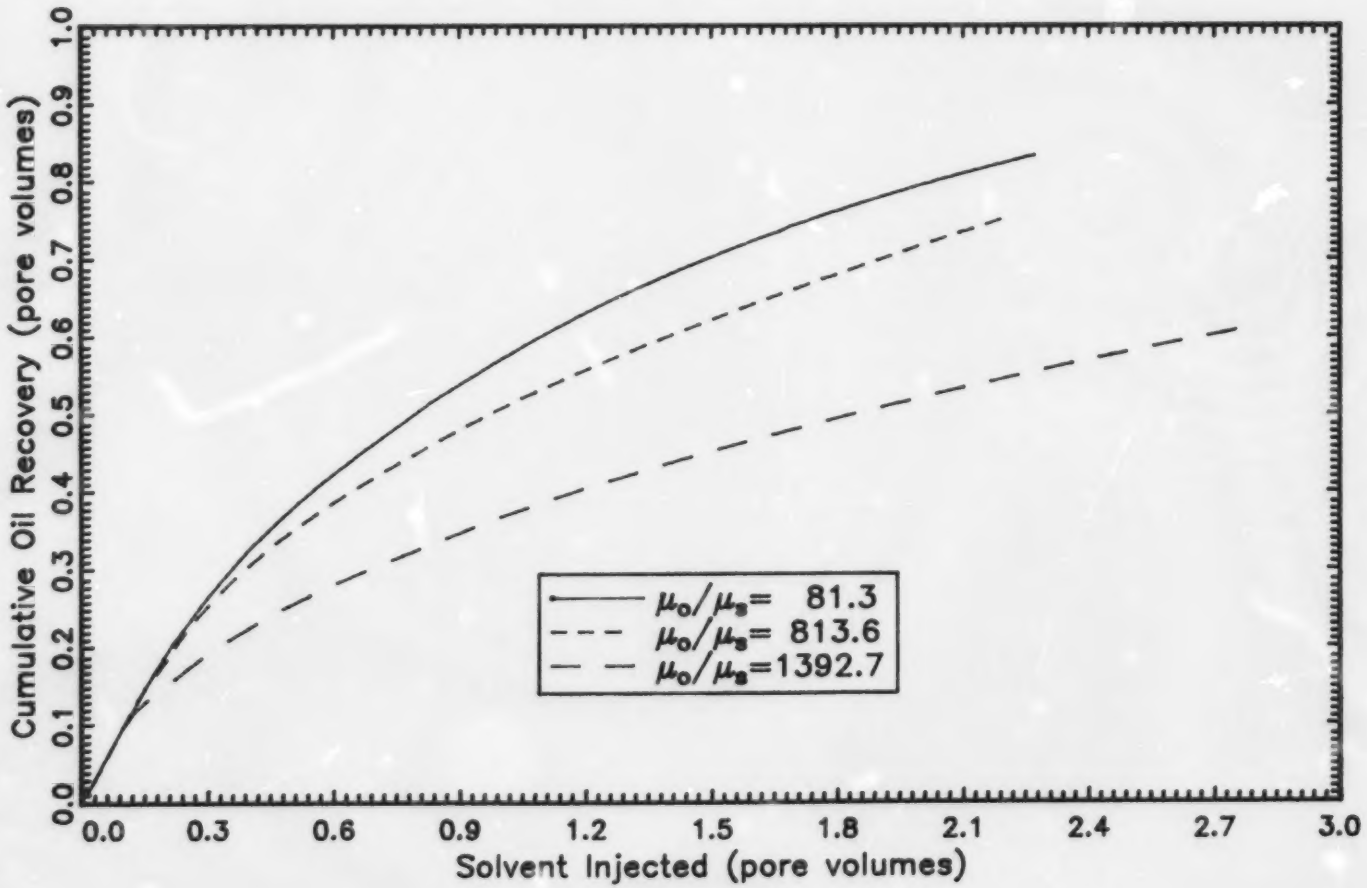


Figure 18: Effect of Viscosity Ratio on Cumulative Oil Recovery
(Miscible Displacement at q = 5mL/min)

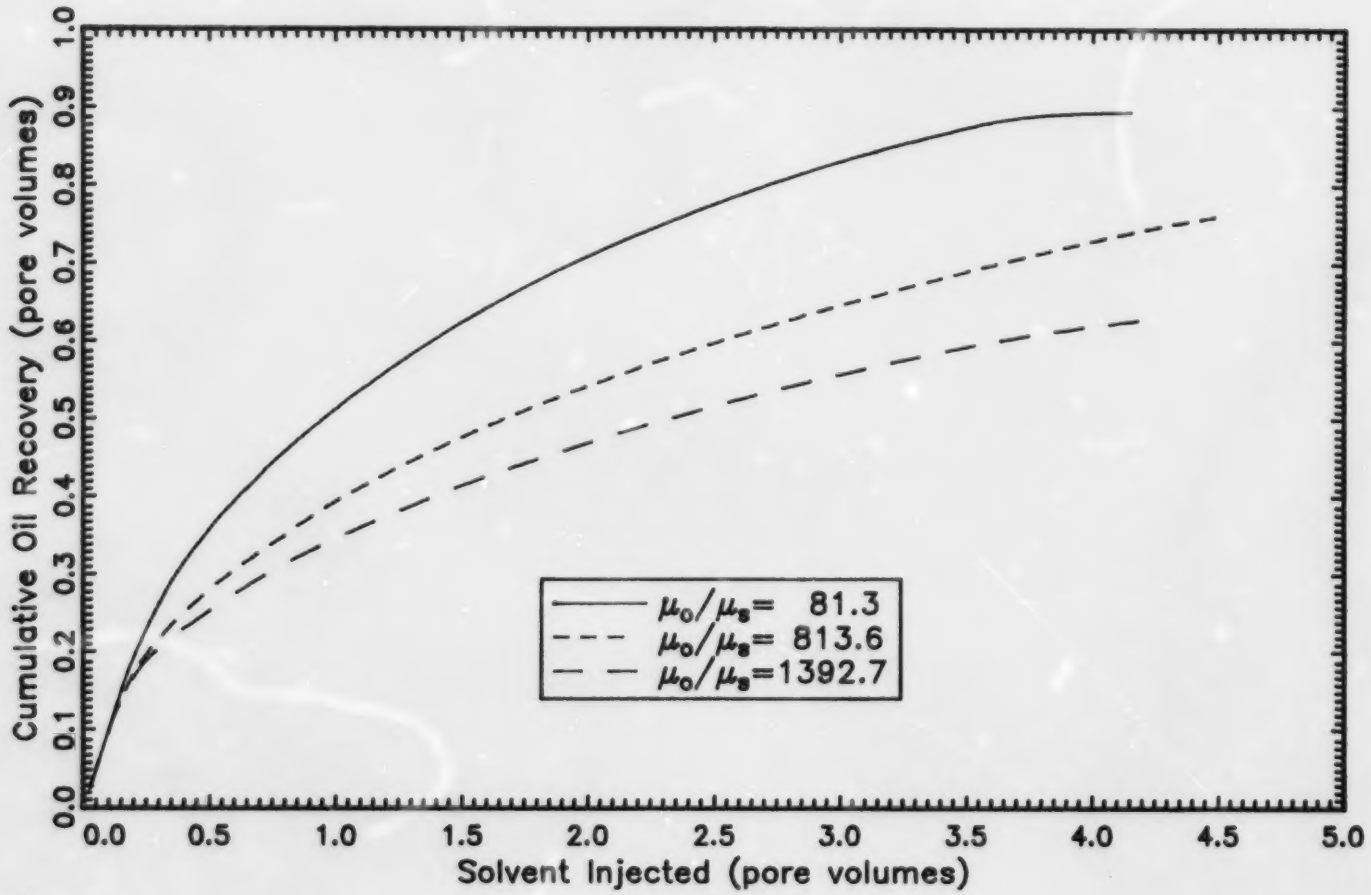


Figure 19: Effect of Viscosity Ratio on Cumulative Oil Recovery
(Miscible Displacement at q = 8mL/min)

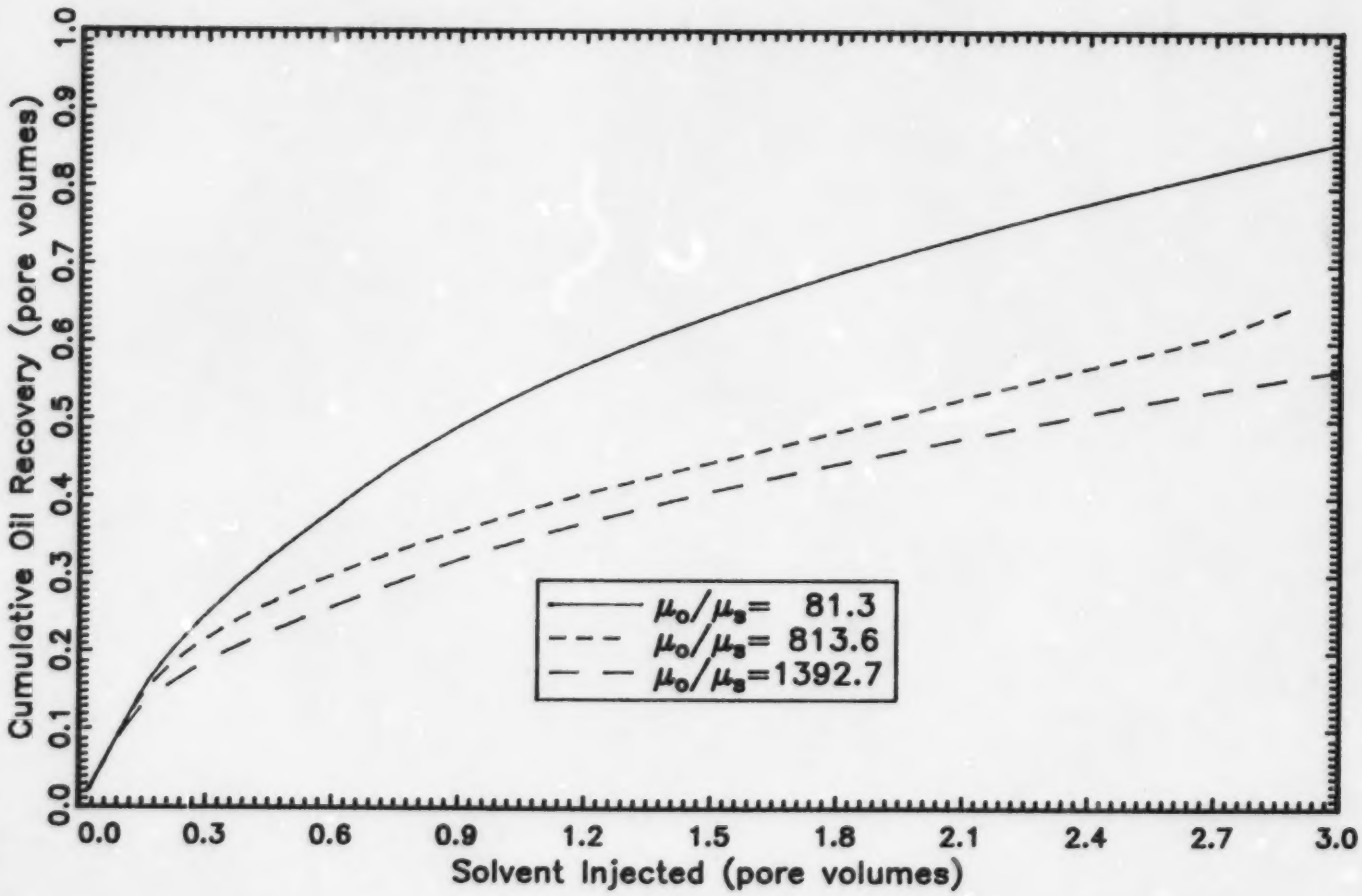


Figure 20: Effect of Viscosity Ratio on Cumulative Oil Recovery
(Miscible Displacement at q = 10mL/min)

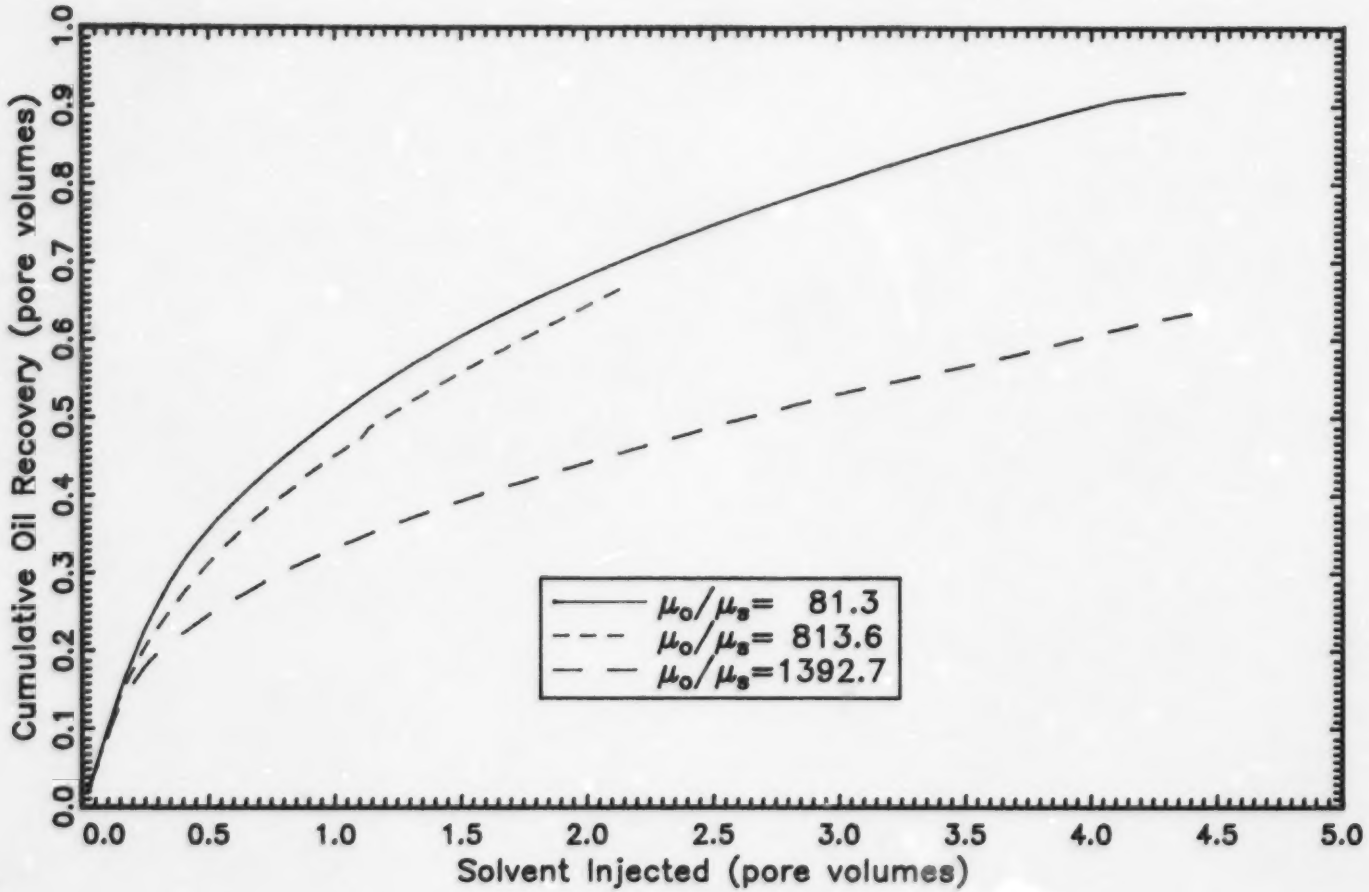


Figure 21: Effects of Displacement Rate on Net Oil Recovery
(Graded–Slug (Claridge) Displacement, Vitrea–22)

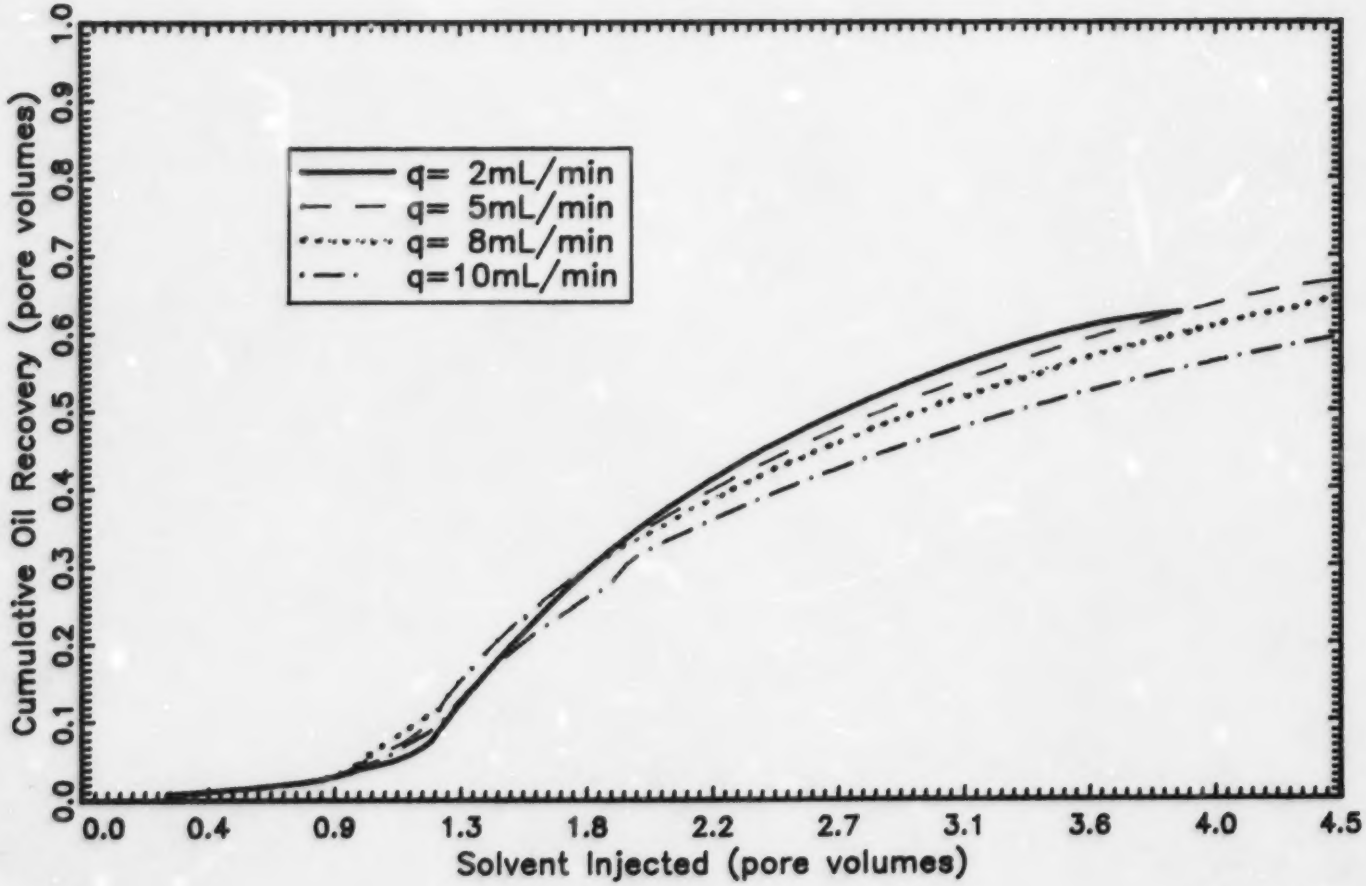


Figure 22: Effects of Displacement Rate on Net Oil Recovery
(Graded–Slug (Claridge) Displacement, Vitrea–150)

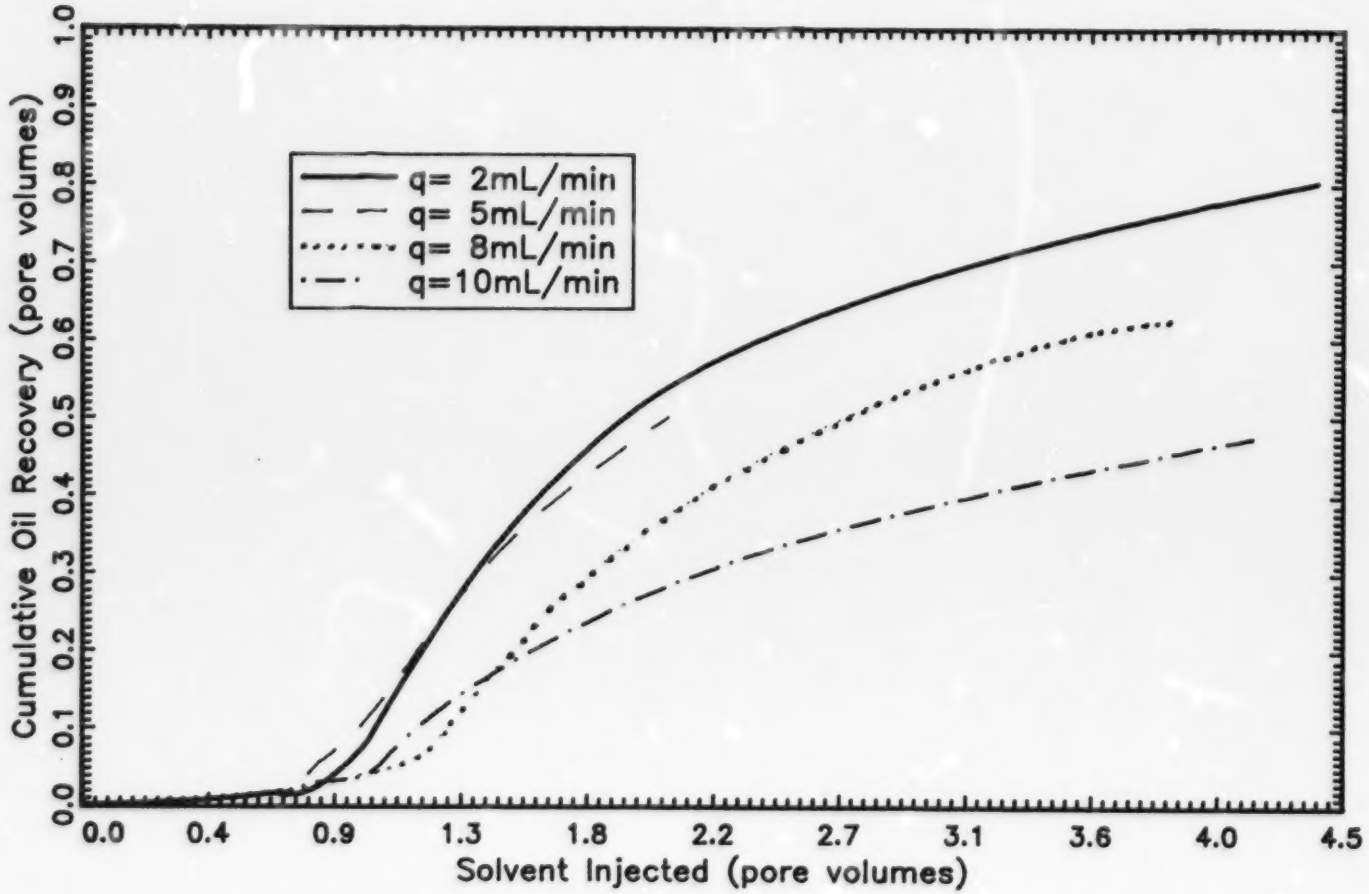


Figure 23: Effects of Displacement Rate on Net Oil Recovery
(Graded–Slug (Claridge) Displacement, Tellus–320)

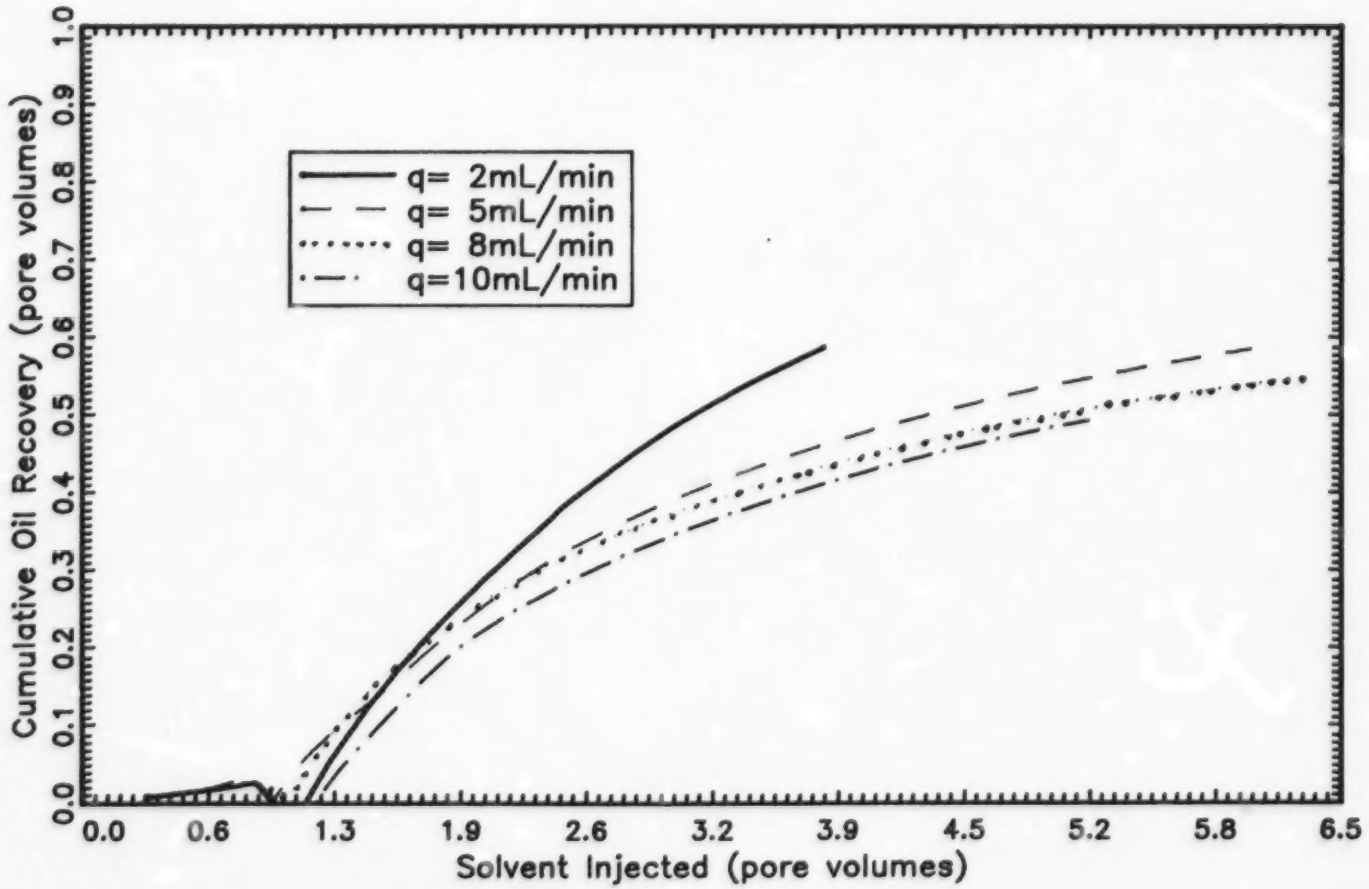


Figure 24: Effect of Displaced Oil Viscosity on Net Oil Recovery
(Graded–Viscosity (Claridge) Slug, q = 2mL/min)

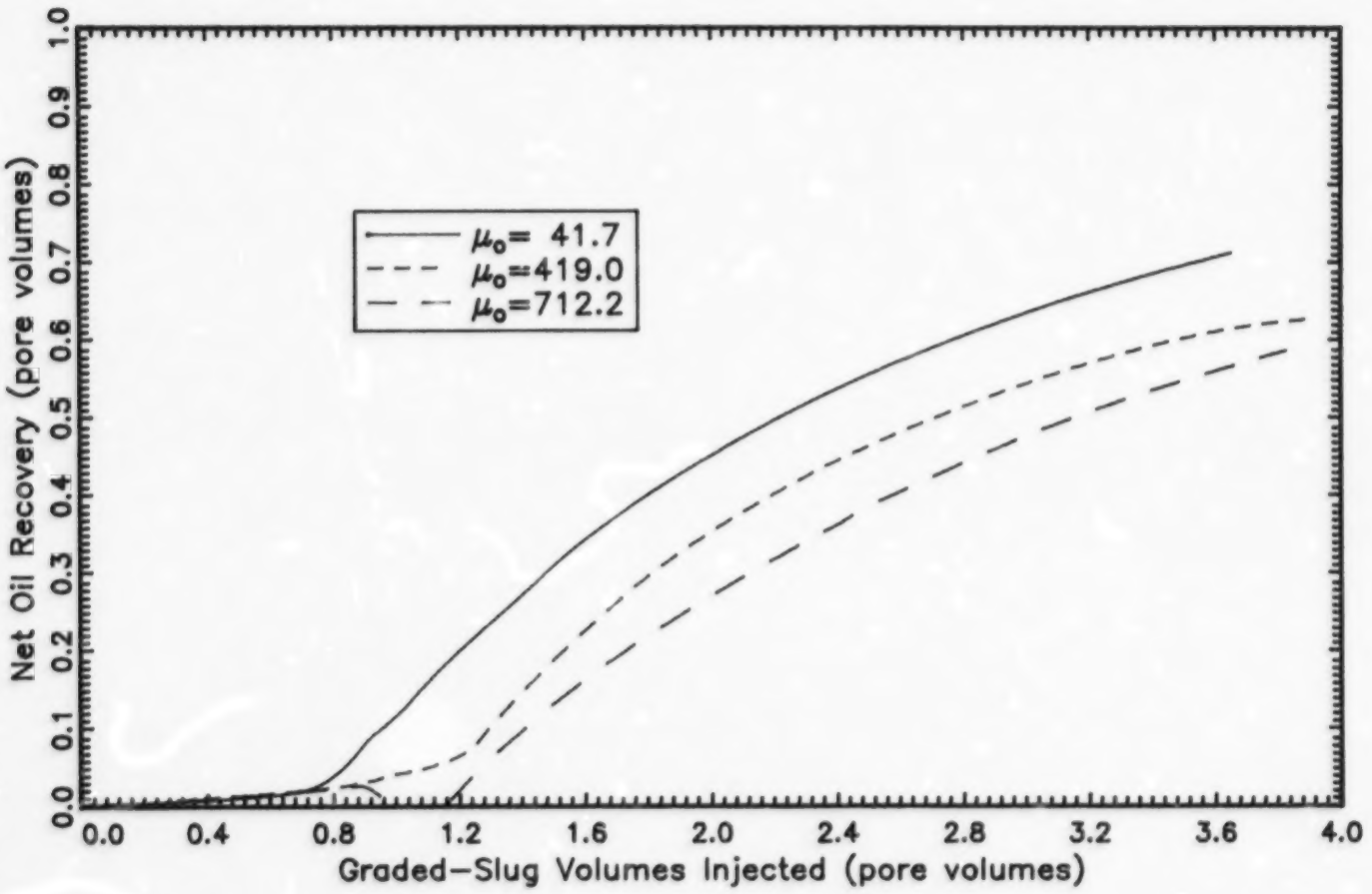


Figure 25: Effect of Displaced Oil Viscosity on Net Oil Recovery
(Graded–Viscosity (Claridge) Slug, q = 5mL/min)

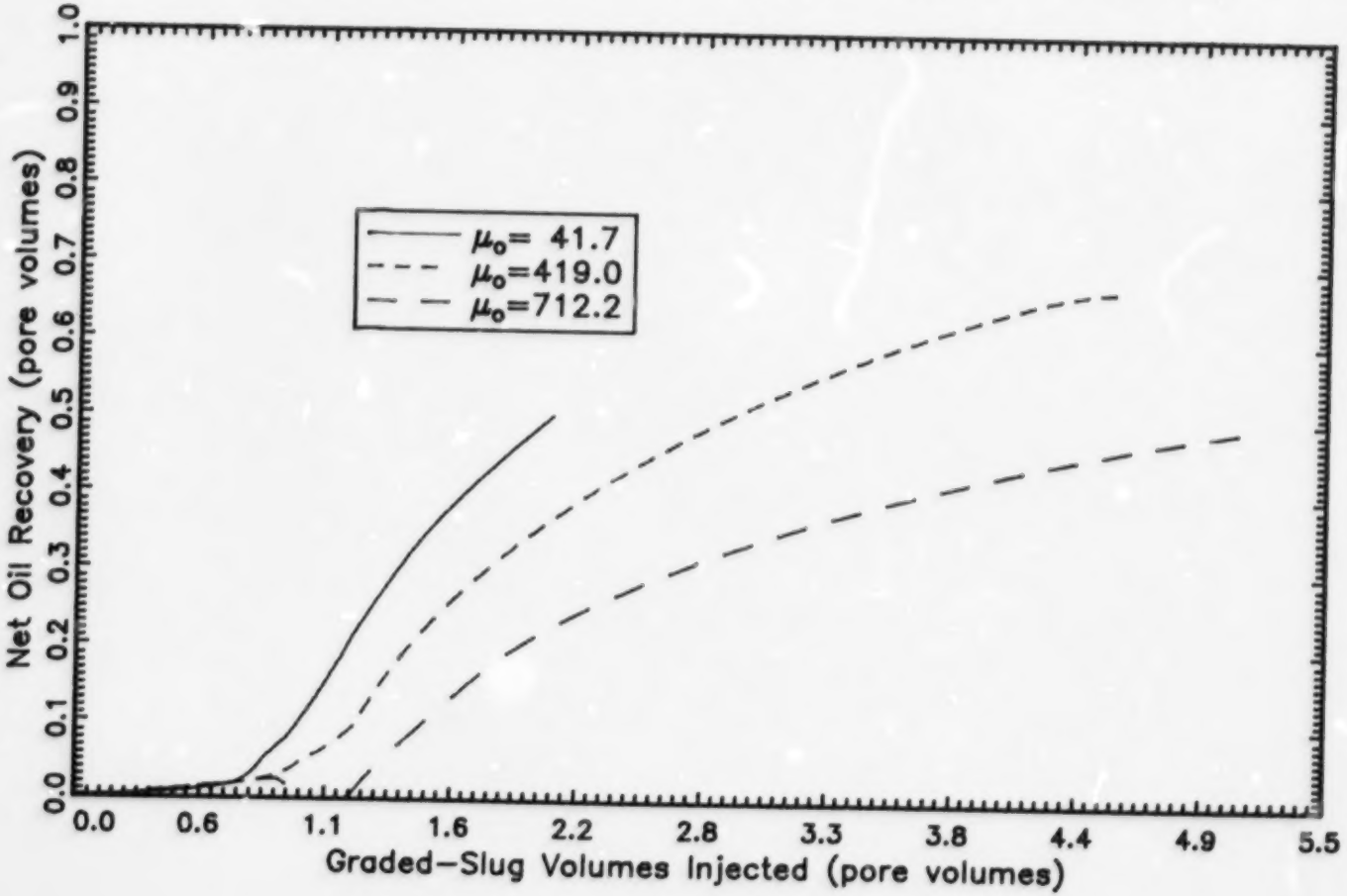


Figure 26: Effect of Displaced Oil Viscosity on Net Oil Recovery
(Graded–Viscosity (Claridge) Slug, q = 8mL/min)

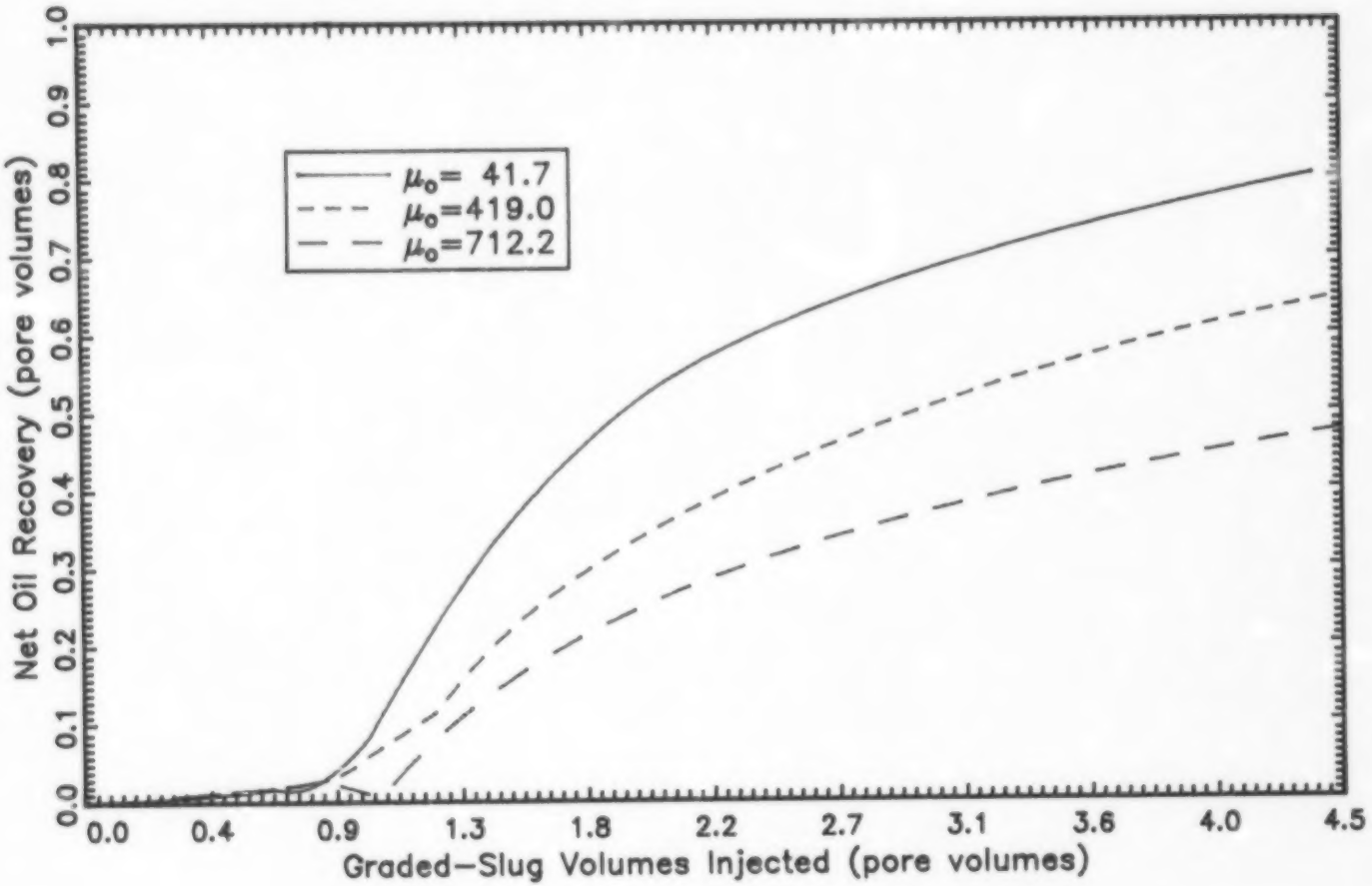


Figure 27: Effect of Displaced Oil Viscosity on Net Oil Recovery
(Graded–Viscosity (Claridge) Slug, q = 10mL/min)

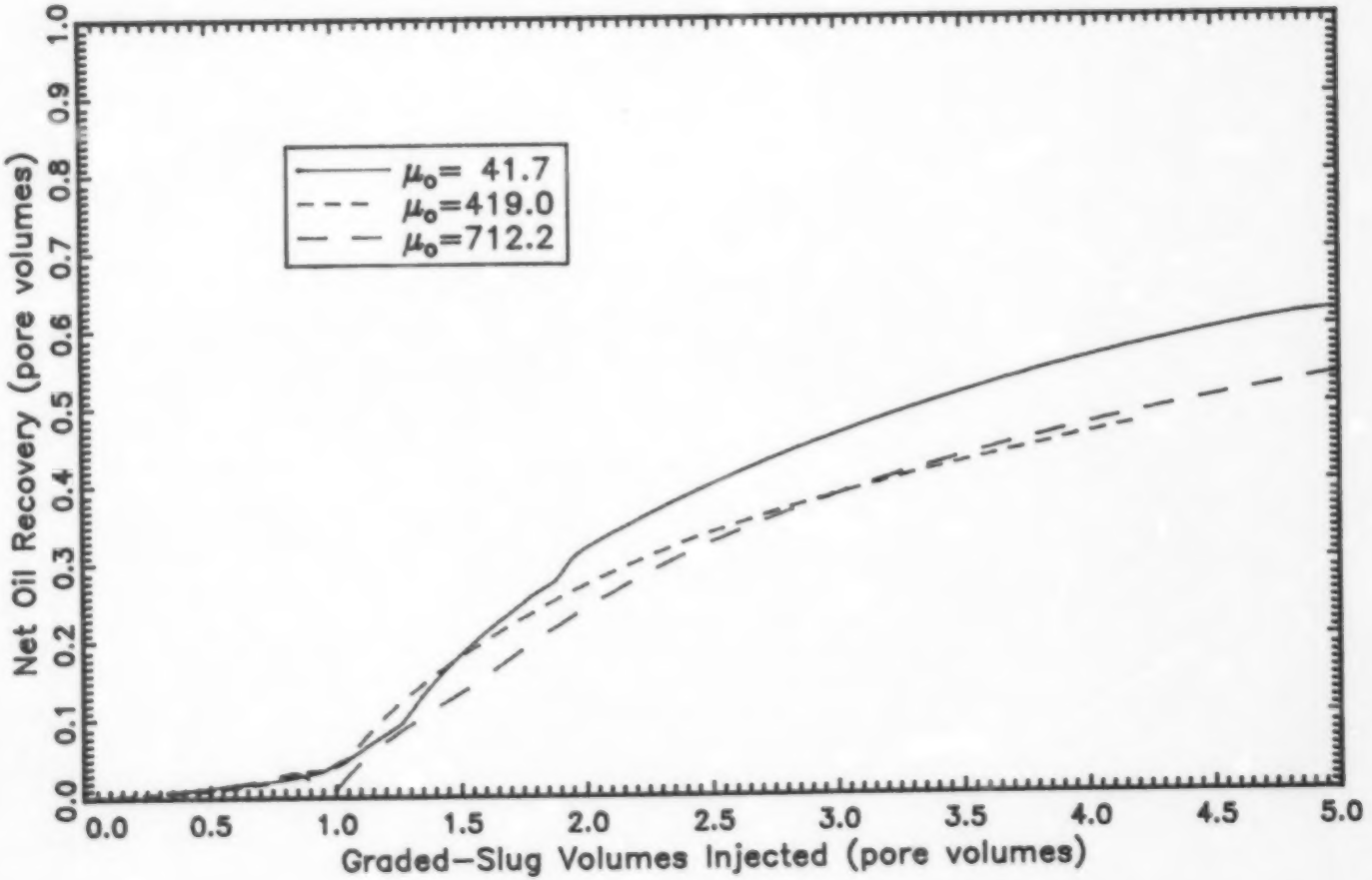


Figure 28: Effect of Displaced Oil Viscosity on Net Oil Recovery
(Linearly Graded–Viscosity Slug, q = 5mL/min)

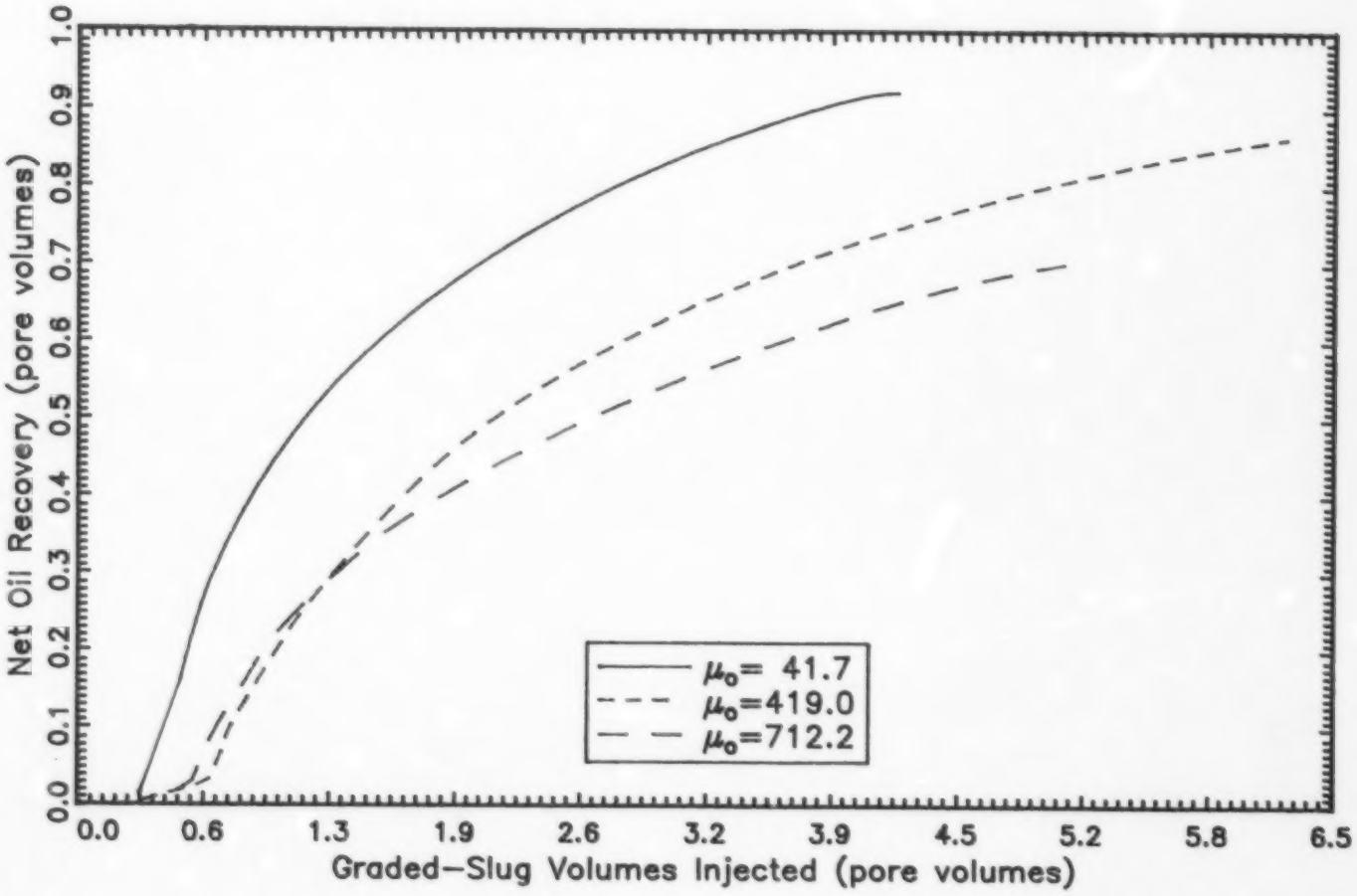


Figure 29: Effect of Viscosity Gradation on Net Oil Recovery
(Vitrea–22 Oil; Flow Rate = 5mL/min)

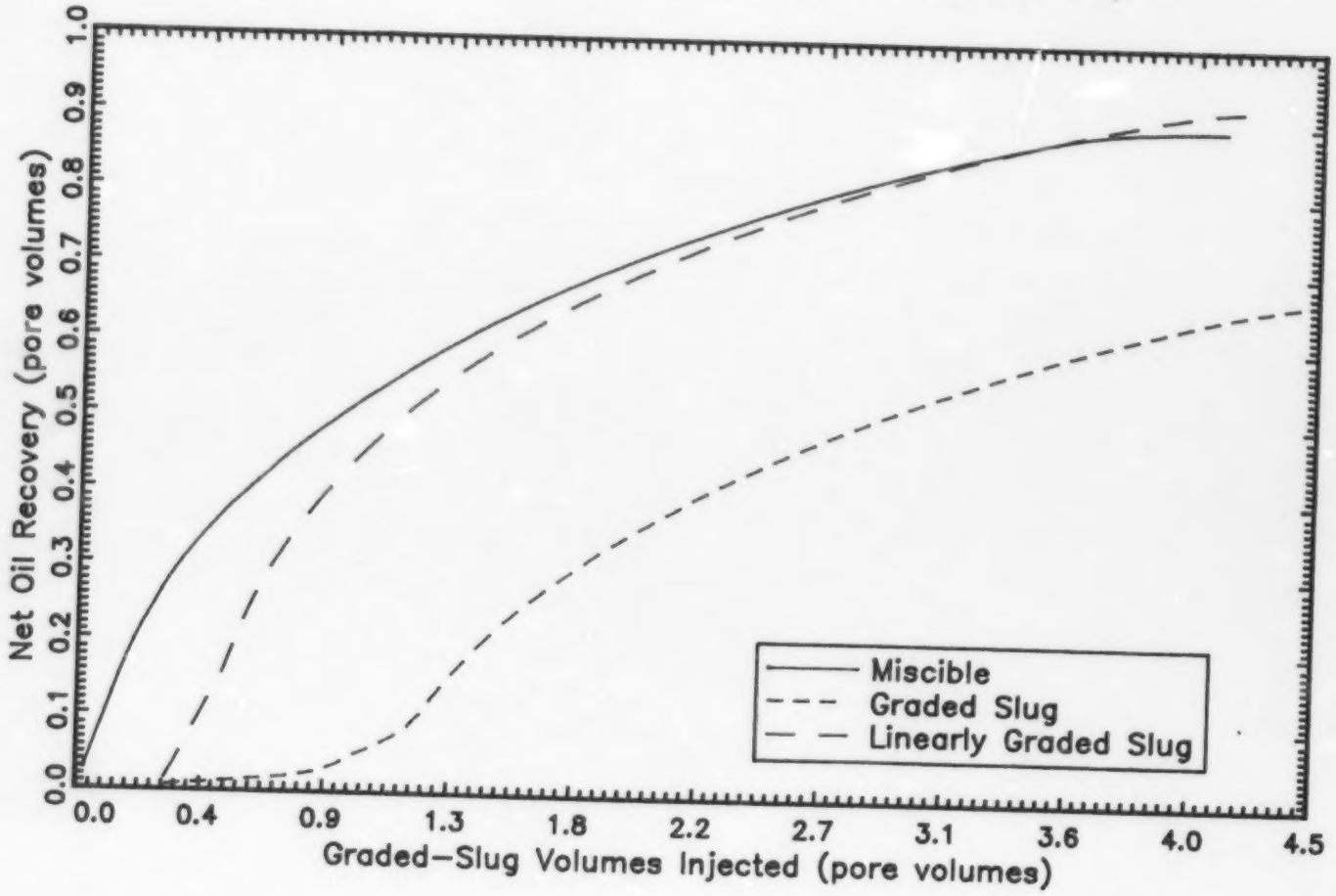


Figure 30: Effect of Viscosity Gradation on Net Oil Recovery
(Vitrea–150 Oil; Flow Rate = 5mL/min)

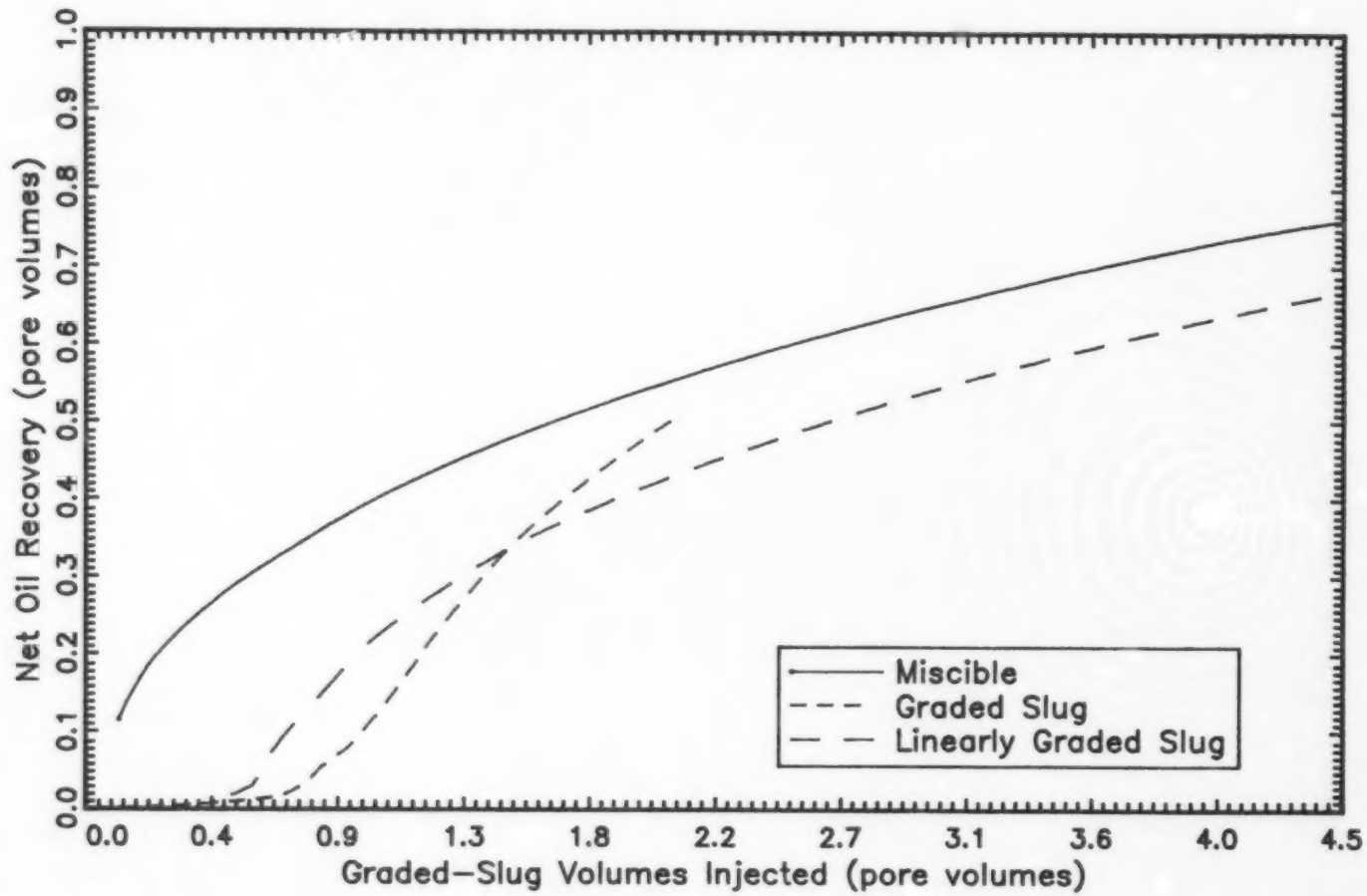
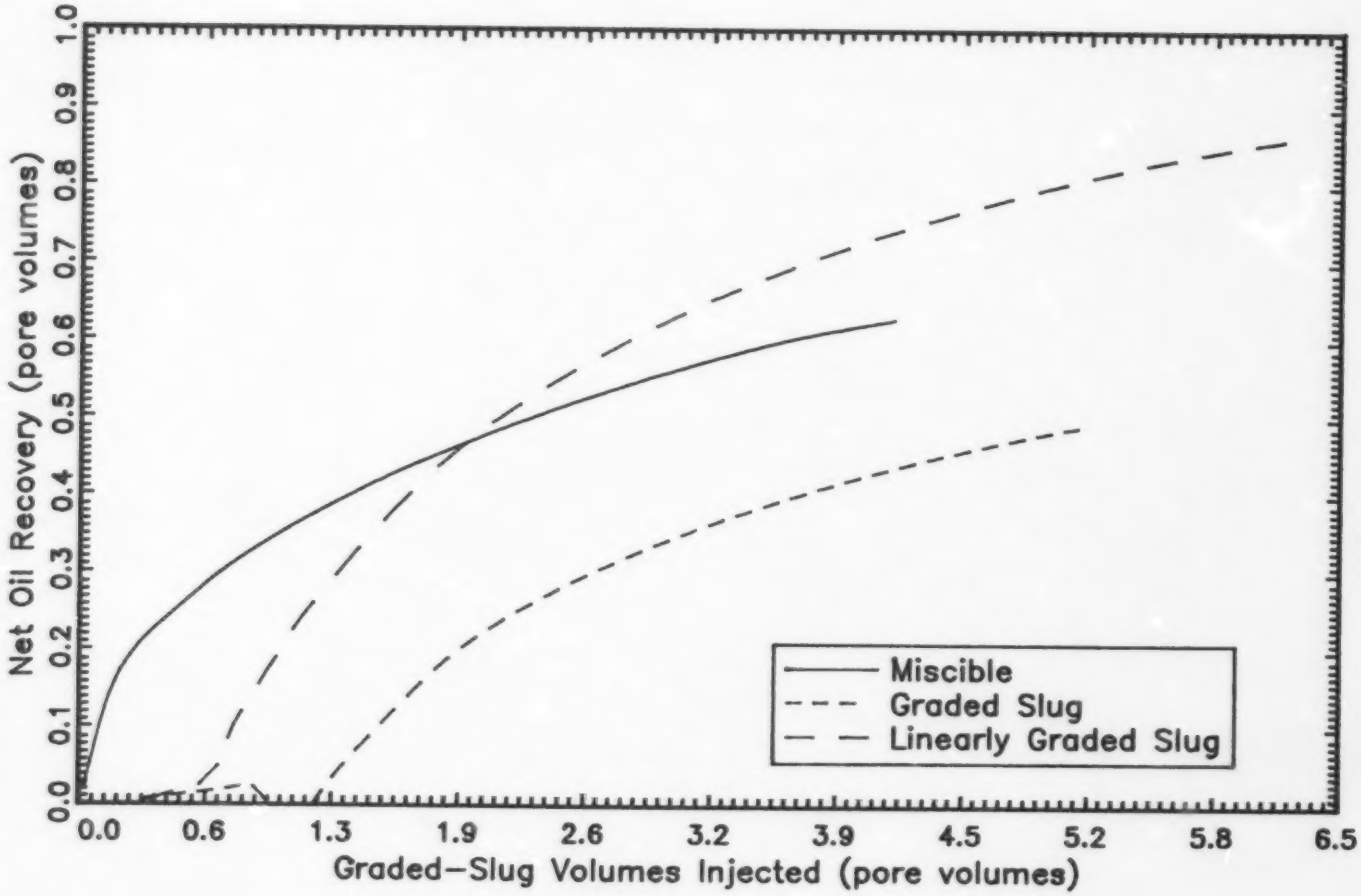
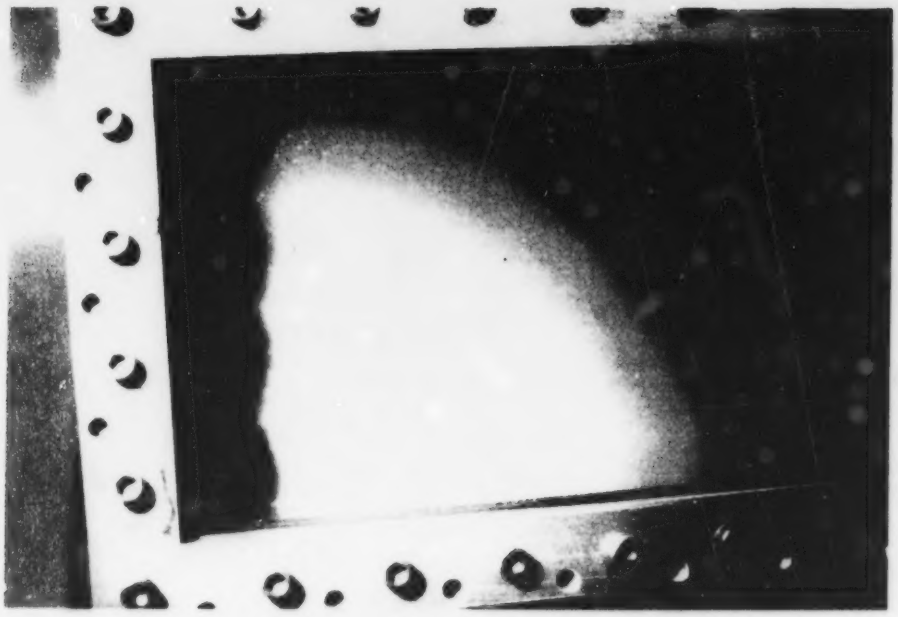
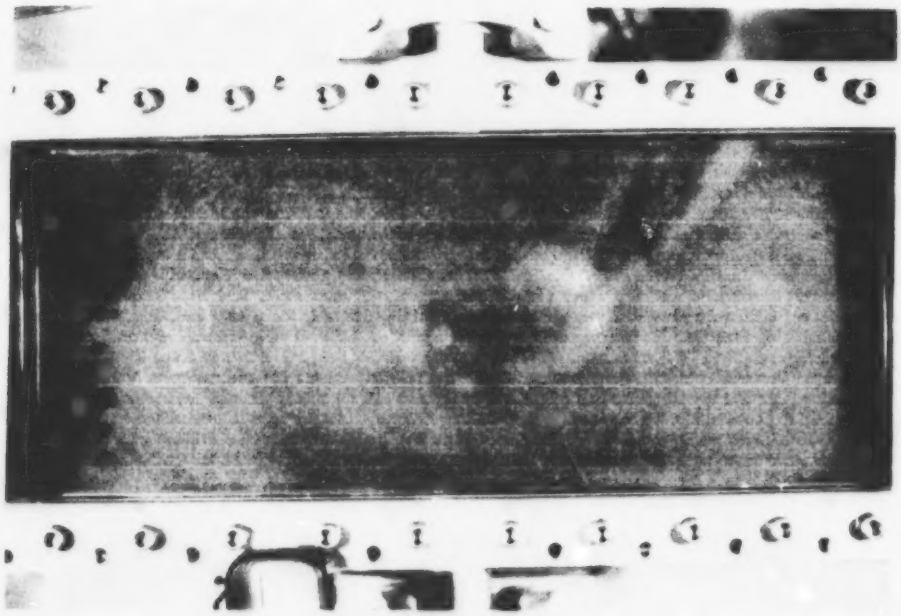


Figure 31: Effect of Viscosity Gradation on Net Oil Recovery
(Tellus–320 Oil; Flow Rate = 5mL/min)

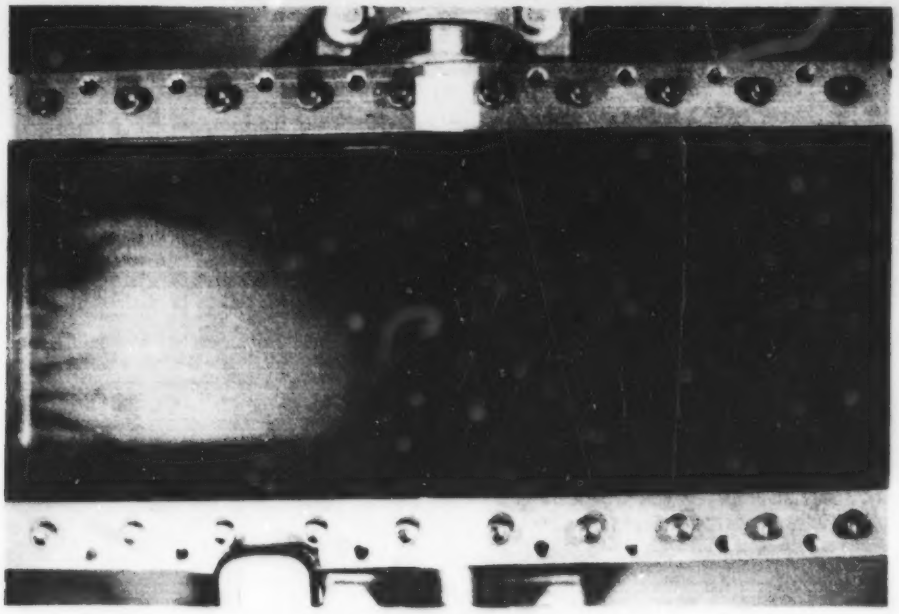




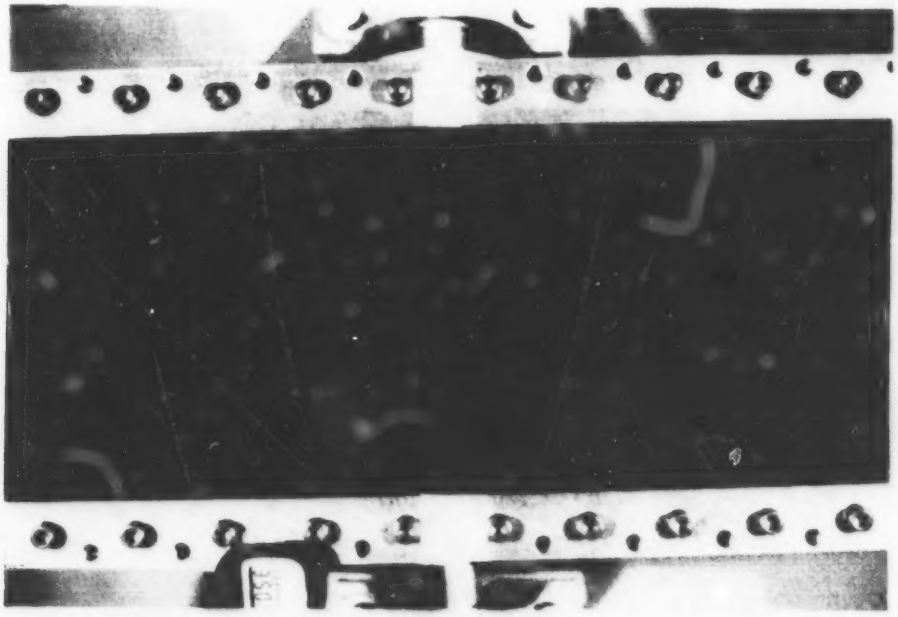
Photograph 1: Homogeneity and Injection-End Effect Test for the Porous Pack



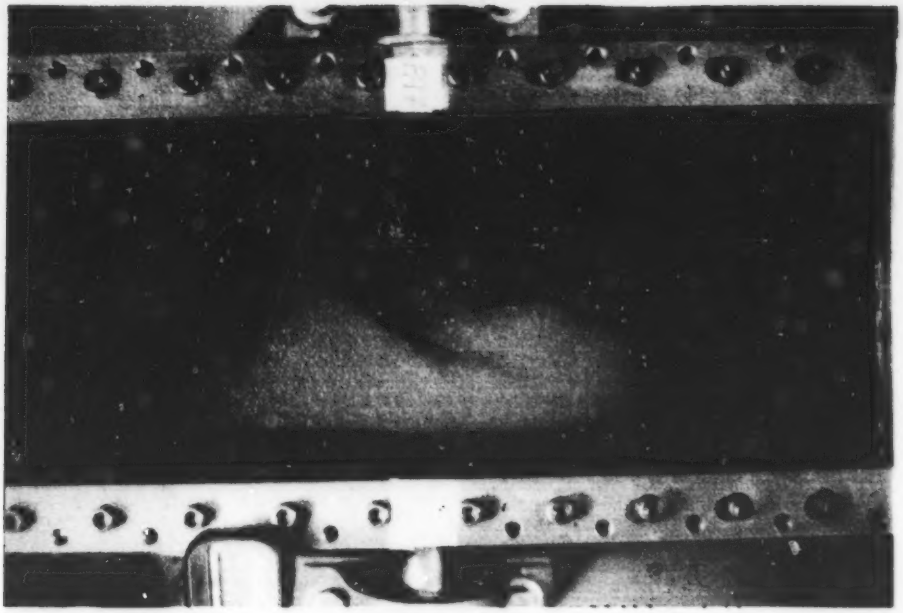
Photograph 2: Viscous F[illegible]ing in a Miscible Displacement (Run 17; Displaced Oil = Tellus-320; t = 129 sec)



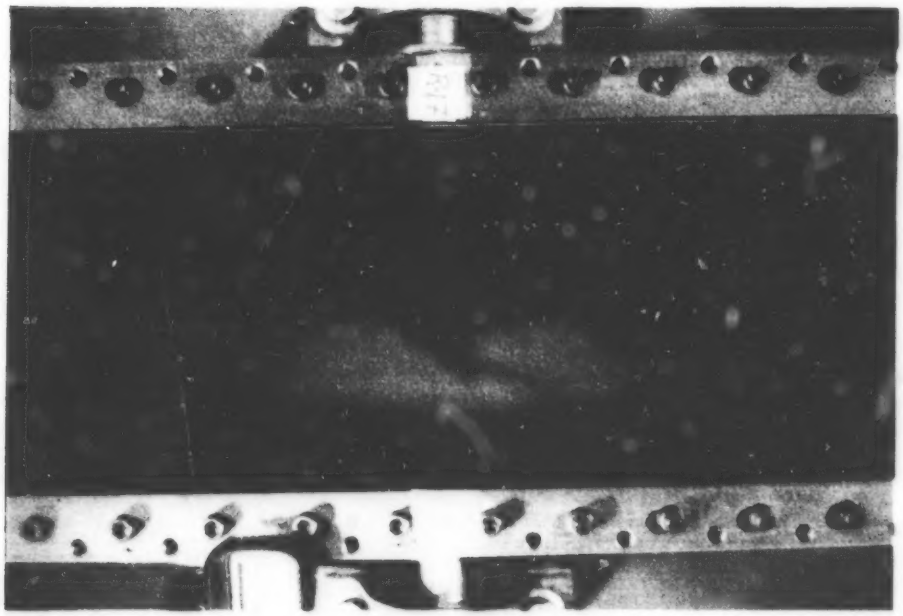
Photograph 3: Viscous Fingering in a Miscible Displacement
(Run 17; Displaced Oil = Tellus-320; t = 148 sec)



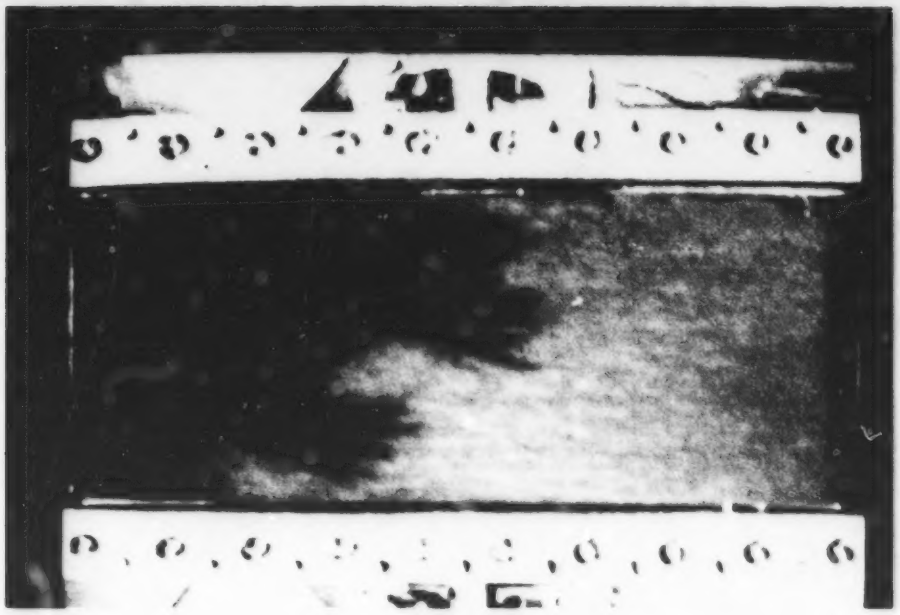
Photograph 4: Viscous Fingering in a Miscible Displacement
(Run 17; Displaced Oil = Tellus-320; t = 230 sec)



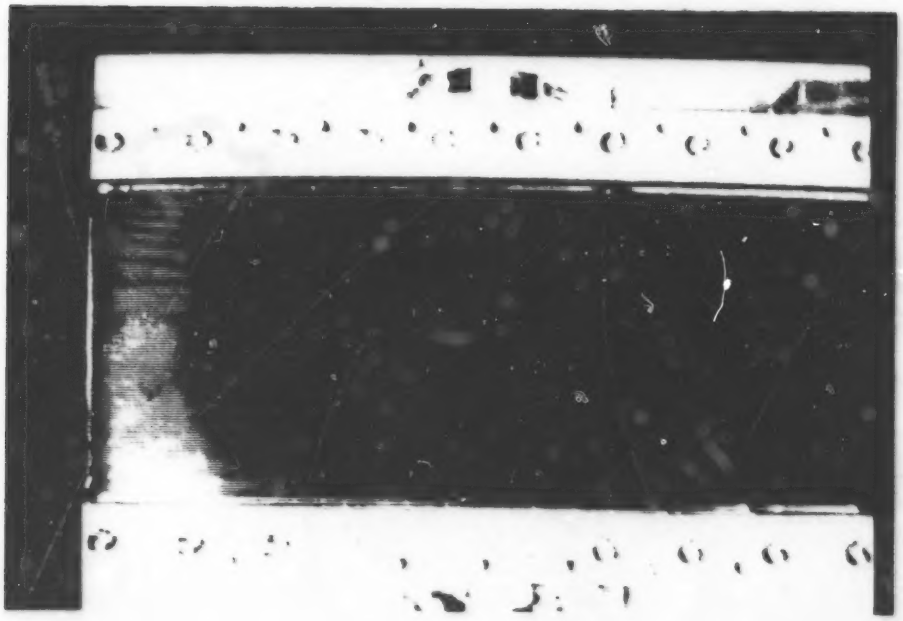
Photograph 5: Viscous Fingering in a Miscible Displacement
(Run 17; Displaced Oil = Tellus-320; t = 276 sec)



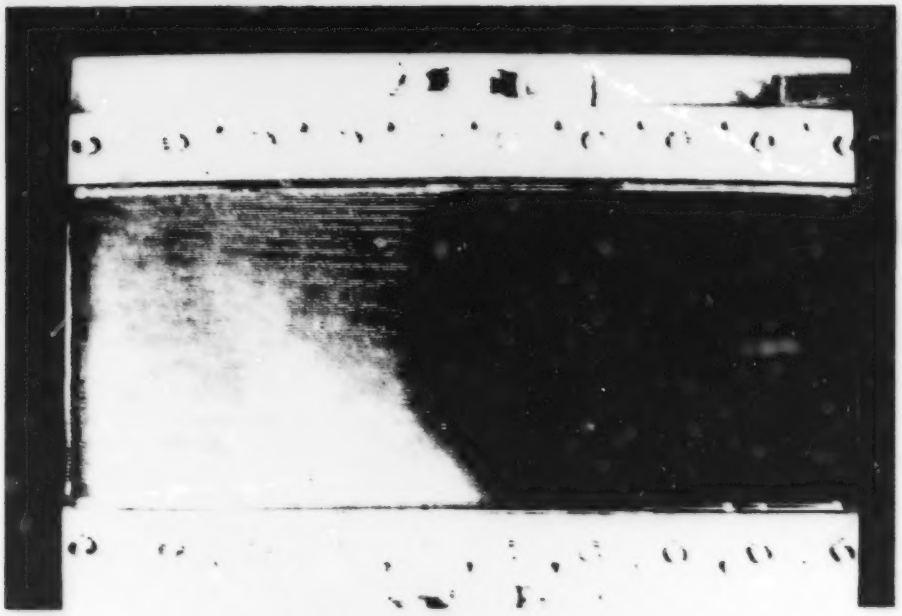
Photograph 6: Viscous Fingering in a Miscible Displacement
(Run 17; Displaced Oil = Tellus-320; t = 313 sec)



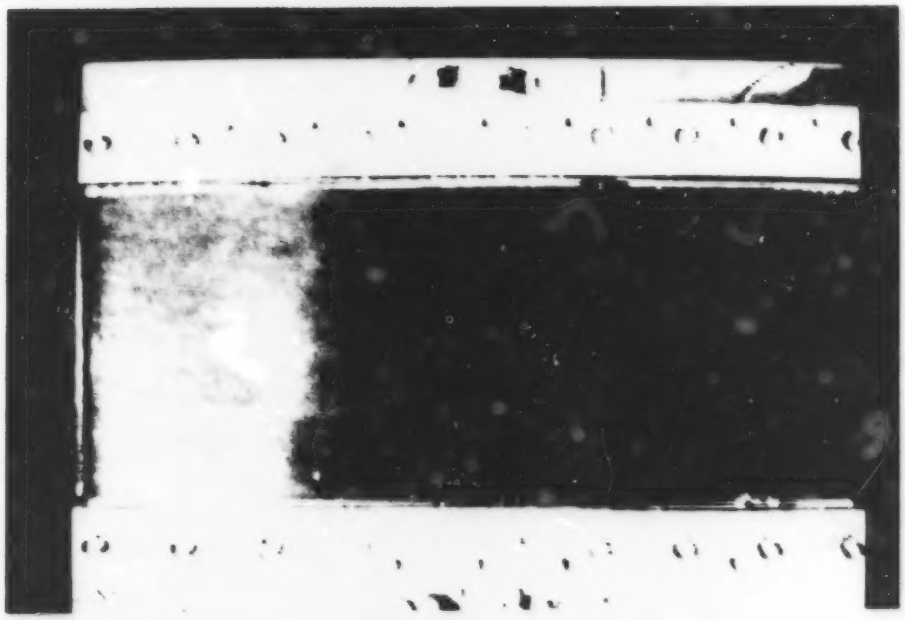
Photograph 7: Viscous Fingering in a Miscible Displacement
(Run 25 ; Displaced Oil = Vitrea-22; t = 230 sec)



Photograph 8: Viscous Fingering in a Graded-Slug Displacement
(Run 28; Displaced Oil = Vitrea-22; t = 9180 sec)



Photograph 9: Viscous Fingering in a Graded-Slug Displacement
(Run 28; Displaced Oil = Vitrea-22; t = 12600 sec)



Photograph 10: Viscous Fingering in a Linearly Graded-Slug Displacement
(Run 30; Displaced Oil = Vitrea-22; t = 15300 sec)